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Abstract

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J.R. Butler

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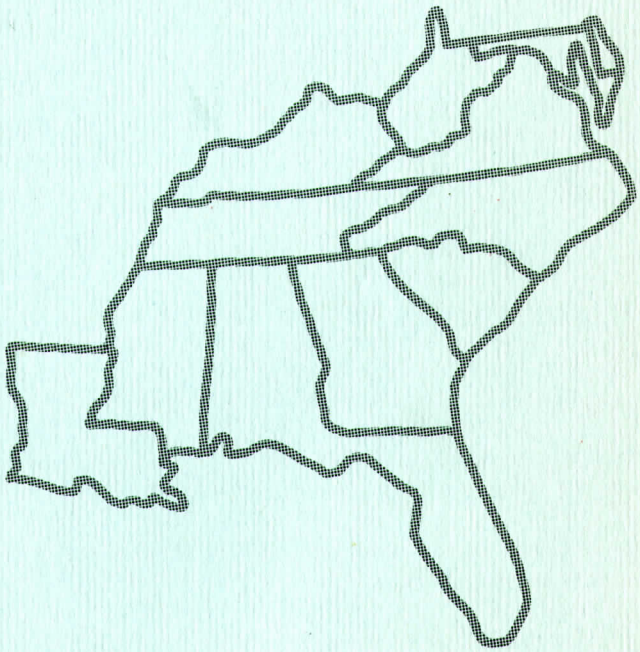

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SOUTHEASTERN GEOLOGY

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1967

SEA-FLOOR STRENGTH OBSERVATIONS FROM THE DRV ALVIN IN THE TONGUE OF THE OCEAN, BAHAMAS

by

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ABSTRACT

The deep research vehicle ALVIN was employed to study the strength of the deep sea sediments in the Tongue of the Ocean. Variously configured free fall test clumps were deployed from a surface vessel. The impact sites of the clumps were then located by the ALVIN by means of light/acoustic beacons attached to the test clumps.

The clumps penetrated approximately three to four inches into the bottom, while the calculated penetration predicted for the clumps ranged from seven to nineteen inches. Much additional work will be required before reliable penetration predictions can be made for cases of dynamic loading of submarine sediments.

INTRODUCTION

Loss of THRESHER in 1962 and the nuclear device off Palomares, Spain, in 1966 acutely dramatized the importance of the strength of bottom sediments as well as the limited extent of our knowledge. In neither case could reliable predictions regarding possible depth of penetration be made until sea-floor observations were made for comparison. A large body of empirical data on sediment strength has been acquired through the years by civil engineers for application of static loading on terrestrial soils and several studies are available on the engineering properties of subaerial sediments and shallow bay sediments (Keller, 1964; Holmes and Goodell, 1964). However, there are only limited data on the engineering properties of deep sea sediments (Richards, 1961, 1962; Busby, 1962; Stiles, 1966) and there are virtually no reported data on dynamic penetration in deep sea sediments.

During September 1966, the U. S. Naval Oceanographic Office leased the deep submergence research vehicle ALVIN in order to perform and evaluate a variety of oceanographic measurements in the Tongue of the Ocean (TOTO), Bahamas. Two of the scheduled 14 dives

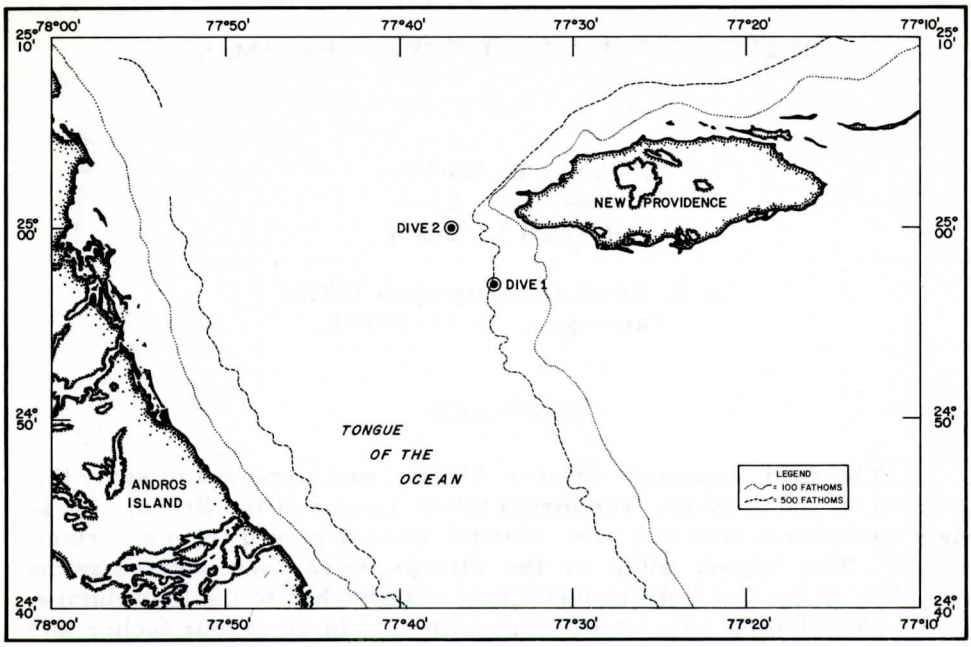


Figure 1. Location of the general impact sites for test clumps deployed on dives 1 and 2. The bottom at the test site for dive 1 was characterized by a ridge and valley system trending normal to the general slope at the bottom. At the test site for dive 2 the bottom was somewhat deeper and virtually flat.

were devoted to bottom strength observations at the locations shown in Figure 1.

Acknowledgments

The writers wish to acknowledge the assistance of Orrin H. Pilkey of Duke University and John R. Carpenter of the University of South Carolina, who critically read the manuscript and offered many helpful suggestions.

PROCEDURE

The bottom strength experiments were designed to record the degree of bottom penetration of free-fall test clumps and to test the feasibility of employing light and acoustic beacons attached to the test clumps as homing devices for a deep research vehicle (DRV). Two test

clumps of different configurations were dropped prior to each dive. The four test clumps are shown in Figure 2 and their dimensions and weights are presented in Table 1. Attached to each clump was a cylindrical shroud to provide stability during descent. A one watt-second strobe light beacon with a two second flash period housed in a sealed glass sphere having a net 6 pound positive buoyancy was attached to each test clump at the end of a 12-foot line. A small 37 KC pinger was attached to the line mounted under the glass spheres. The clumps and stabilizing shroud were red-white striped at one inch intervals to provide a visual method of determining bottom penetration.

Clumps 1 and 2 were deployed for the first dive on 1 September. The second dive scheduled for 2 September was cancelled subsequent to deployment of test clumps 3 and 4 and was not completed until 6 September.

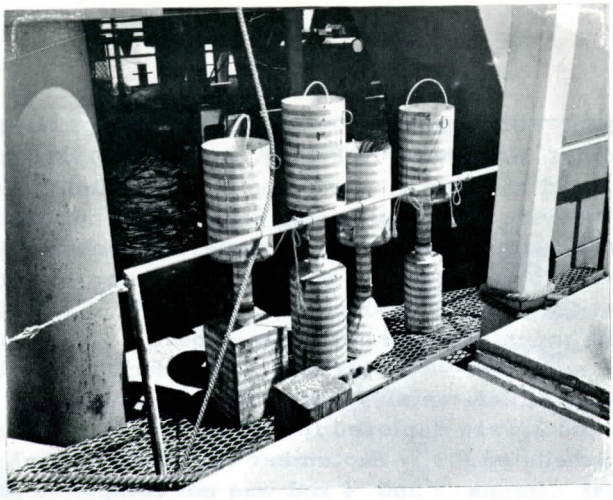
Table 1. Bearing Capacity Data

Shape	Dimensions w x l x h (ft.)	Buoyant Weight* (lbs.)	Kinetic Energy (ft.-lbs.)	Dynamic Penetration (ft.)	Penetration Ratio** Predicted/observed
1. Prism	1.0 x 1.0 x 1.5	180.5	549	0.64	2.6
2. Inverted cone	1.2 dia. x 1.0	90.5	275	0.28	1.1
3. Cylinder	1.0 dia. x 2.0	176.5	537	0.80	3.2
4. Cylinder	0.75 dia. x 1.5	96.5	293	0.77	3.1

* Total weight (clump and stabilizing canister in water)
** Based upon an observed penetration of 0.25 ft.

OBSERVATIONS

During the first dive the acoustic signals from the 37 KC pingers attached to clumps 1 and 2 were detected on ALVIN's scanning sonar immediately upon submergence. Bottoming at 3,400 feet, ALVIN homed in on the pingers through bearings obtained on the CTFM (Continuous Transmission Frequency Modulated) sonar and proceeded directly to the impact site where clump 2 was observed. The light beacon of clump 2 was located visually after traveling a short period along an acoustically acquired heading.



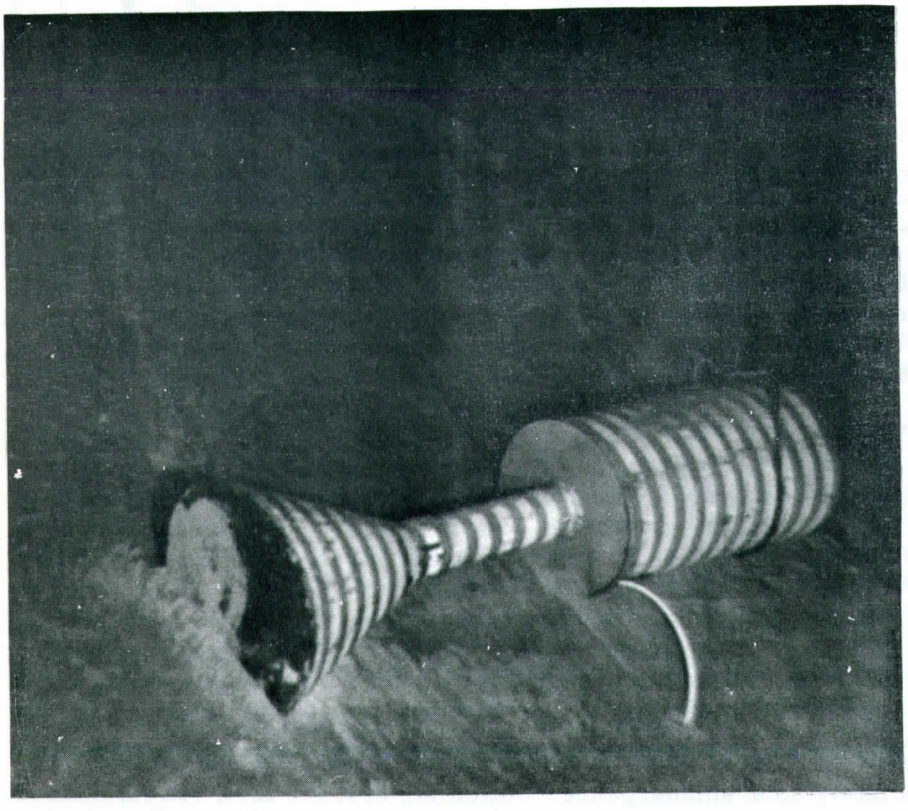


Figure 2. (Upper) The four free fall test clumps are shown lashed on the catamaran pontoon of the surface tender LULU. (Lower) Underwater photograph taken from the ALVIN shows the attitude of test clump 2 on the sea floor.

The impact site of both clumps was an area of considerable local relief characterized by a ridge and valley system trending normal to the TOTO marginal escarpment and presenting slope angles up to 45 degrees. Clump 2 was found on the more gently sloping flank (15°) of a large ridge a few feet below the crest. The clump was not standing upright but had fallen over and rolled about 15 feet down the slope (Figure 2). A circular indentation approximately 3 inches deep marked the exact impact site. A three or four inch deep scar running from the circular indentation down slope to the edge of the conical test clump marked the trail of the clump as it rolled down the slope. The conical clump came to rest on its side with the circular edge of its base buried four to five inches into the sediment. Photographs of the clump and indentations were taken from various angles and a short sediment core was collected to permit determination ashore of the vane sediment shear strength.

The flashing strobe on the float of clump 1 was visually sighted while still on station at the impact site of clump 2 some 130 feet distant. Clump 1, a rectangular prism with square impact face, came to rest in the valley formed by the steep slope of the ridge upon which clump 2 was found and the flank of the adjacent ridge. The canister shroud of the test clump was down slope and was nearly half full of sediment. An unsuccessful search was made for an indentation marking the impact site. Obviously, this area was not an ideal choice of terrain for these experiments and the remainder of the bottom time during this dive was devoted to a search for a more satisfactory test impact site.

As ALVIN moved away from test clump 1, the distance to the clump was measured periodically by sonar. At distances of over 100 yards no reflection could be observed on the sonar display and consequently no accurate measurement of the limits of visual detection of the flashing 1 watt-second beacons was determined. The flashing beacon was sighted later from the crest of another ridge at a distance well beyond the 100 yard range of the sonar reflection.

The second dive was delayed until 6 September although cylindrical clumps 3 and 4 had been deployed on 2 September. The life expectancy of the strobe light battery was 40 hours and approximately 170 hours for the pinger battery. It was expected that it would be necessary to locate the impact site of the clumps without the assistance of the visual beacons. On 6 September, the second site of deployment was re-occupied. The signals from the 37 KC pingers on the clumps were detected with the directional hydrophone mounted beneath the tender and an attempt was made to locate the impact site acoustically. Both clumps were located with relative ease and were separated by only 20 feet on the relatively flat bottom. Unexpectedly, the strobe beacons were still flashing with a period of approximately 30 seconds. Both clumps were found lying on their sides; however, judging from the circular 4-inch deep indentation in the sediment, near where found, both clumps apparently struck the bottom on the circular impact face of the solid cylinders.

DISCUSSION

Shear strength values for surficial sediments in the vicinity of the test site have been published by Busby (1962). Busby's shear strength values in terms of cohesion range from 0.2 to 1.0 psi in the general impact area and compare favorably with values of 0.5 to 0.7 psi which were obtained from the sediment sample collected during the first dive at the impact site of clump 2. On the basis of these values, an average value of 0.6 psi (86.4 psf) was used for all calculations of dynamic bearing capacity of the sediment. All calculations are based on an impact velocity of 13 ft/sec which is the terminal velocity determined for the Benthos boomerang corer which has a configuration similar to that of the test clumps.

The method used for predicting test object penetration was similar to that employed by Ocean Science and Engineering, Inc. (1963) in studies of the THRESHER search operations. Calculations of test object penetration were based on the following equation:

$$KE = B_D A P$$

where KE is kinetic energy (ft.-lbs.), B_D is dynamic bearing capacity (lb./ft.^{2}), A is the basal area of the test object (ft.^{2}), and P is the depth of object penetration (ft.). This equation relates the energy available prior to object impact with the amount of work done during penetration.

Kinetic energy was computed from one-half the product of the velocity squared and the buoyant weight of the test object divided by the gravitational constant. Bearing capacity (B_D) is defined as the average load per unit of area required to produce failure by rupture of a supporting sediment (soil) mass (ASCE, 1958). For static foundation investigations, the formula for predicting the bearing capacity for cohesive saturated sediments consists principally of two parts, the shear strength in terms of the cohesion and a bearing capacity coefficient. The product of these two factors constitutes the bearing capacity. Some bearing capacity formulae take into account such factors as object shape and sediment density; however, these present only slight changes in the total value and are commonly not included. Bearing capacity coefficients ranging from about four to eight are commonly used in static foundation investigations (Taylor, 1948; and Tschebotarioff, 1951), however, very little information is available which relates a static loading condition to the dynamic case. Experiments conducted by Ocean Science and Engineering, Inc. (1963) indicate that penetration under dynamic conditions ranges between one and three times that of static applications. Based on these experiments they found that a value of ten for the dynamic bearing capacity coefficient was reasonable. A similar value was used in this investigation. The product of this value (Nc = 10) multiplied by the average shear strength (86.4 lbs./ft.^{2}) gives an average dynamic bearing

capacity of 864 lbs. /ft.^{2} for the sea floor at the sites investigated in this study.

Ratios of predicted and observed penetration values, shown in Table 1, range from 1.1 for the inverted cone clump 2 to 3.2 for the large cylinder clump. These ratios suggest that the bearing capacity coefficient for dynamic load applications should be somewhat increased to more closely predict actual penetration values. The shear strength for these dominantly carbonate sediments may not be solely a function of cohesion or the electrochemical forces of attraction but rather the sum of several factors such as pore pressure, friction, and cementation plus cohesion.

SUMMARY

The results of these two dives point up two important observations. First, the relative ease with which the ALVIN proceeded directly upon bottoming to the impact sites demonstrates the utility of employing light/acoustic beacons to facilitate DRV search and location operations of free-fall instrumentation packages. Such beacons in addition can serve as a navigational reference and can be used for marking and relocating underwater hardware. Second, a comparison of predicted versus observed penetrations demonstrates that the approach for prediction of dynamic object penetrations used in this investigation is well within an order of magnitude difference from visual observations. However, much additional work is required to provide reliable estimates of penetration under dynamic loading conditions in submarine sediments.

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NICKELIFEROUS SOILS AND STREAM SEDIMENTS ASSOCIATED WITH PERIDOTITES NEAR DEMOCRAT, NORTH CAROLINA

by

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and
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ABSTRACT

Two analytical procedures for nickel are employed in the analysis of soils and stream sediments in the vicinity of two peridotites near Democrat, North Carolina. Both procedures utilize dimethylglyoxime but differ in the method of sample digestion. Samples are digested in a buffered ammonium citrate solution ("available" nickel procedure) and in a 1:3 nitric acid solution ("total" nickel procedure).

Lateritic soils overlying peridotite analyzed by the "total" nickel procedure generally contain 1,000 to 10,000 ppm nickel, whereas soils overlying adjacent country rocks generally contain less than 30 ppm nickel. The "available" nickel concentration in soils overlying peridotite ranges from 10 to 25 ppm, and the adjacent soils contain less than 5 ppm. Both methods appear to be applicable in delineating covered peridotites.

The indicated background values for stream sediments derived from sources other than peridotites are less than the limit of detection of the "total" nickel procedure (< 25 ppm). Anomalous values range from 25 to 420 ppm nickel. Stream sediment anomalies extend from 1,000 to 4,000 feet downstream from the peridotites. Values determined by the "available" nickel procedure are low (< 8 ppm) and show poor correlation with those determined by the "total" nickel procedure. Hence, the "total" nickel procedure is potentially applicable in stream sediment exploration for lateritic nickel deposits in western North Carolina, but the "available" nickel procedure shows little promise.

INTRODUCTION

This paper describes the dispersion pattern of nickel indicated by analyses of 18 soil samples and 43 stream sediment samples in the vicinity of two peridotites near Democrat, North Carolina. This area was selected for study because the stream pattern permitted testing of a variety of drainage conditions for the downstream limit of detection

of known nickel concentrations. The applicability of modern geochemical methods in the exploration for lateritic nickel deposits in the Blue Ridge area is evaluated.

Peridotites and residual soils developed from peridotites contain anomalous amounts of nickel compared to the average crustal abundance of this element. According to Worthington (1964) the nickel content of the unweathered peridotite in the Blue Ridge area is rarely less than 0.2 percent and ranges as high as 0.4 percent. The average nickel content of igneous rocks is 0.01 percent (Green, 1959).

Nickeliferous soils developed on certain peridotites in western North Carolina are considered to represent true laterites which formed mainly during periods of intensive weathering of Early Tertiary, and possibly Late Cretaceous age (Worthington, 1964). The formerly extensive lateritic soils are only partially preserved in the present period of active erosion.

Lateritization of peridotite involves leaching of magnesium and calcium and enrichment of the less mobile elements nickel, iron, aluminum, chromium, cobalt, and manganese. Silica may also be leached, although silica enrichment is commonly evident in the lower portions of the soil profile. Additional enrichment of nickel results from leaching of nickel in the upper part of the soil profile and subsequent reprecipitation in lower zones as a hydrous nickel silicate of the garnierite group. As a result of nickel enrichment during weathering, the nickel content of soils commonly exceeds 1 percent. Erosion and solution weathering of soils and bedrock disperse the nickel to the stream sediments. Detailed discussions of the chemical behavior of elements in the lateritization of peridotites are given by De Vletter (1955), Von Gaertner (1963), and Hotz (1964).

Acknowledgments

The authors are grateful to J. M. Fagan, R. W. Johnson, Jr., J. M. Kellberg, R. A. Laurence, Helmuth Wedow, Jr., and J. E. Worthington for editing the paper. Thanks are also extended to G. D. Robinson who assisted in sample preparation. This paper is published with the permission of the Tennessee Valley Authority.

PREVIOUS WORK

Most of the published geologic investigations of peridotites in western North Carolina are descriptions of economic mineral occurrences. These include olivine, chromite, corundum, nickel, anthophyllite asbestos, talc, and vermiculite.

In the Democrat area, Hunter (1941) and Hunter, Murdock, and MacCarthy (1942) present detailed geologic maps and descriptions of

olivine and chromite occurrences associated with two peridotites. Additional information is included in an unpublished TVA report by Hunter, Broadhurst, and Robinson (written communication, 1940). Brief descriptions of nickel mineralization at the Democrat deposit are presented by Eckel, Hunter and Mattocks (1938). Of particular interest is a recent article by Worthington (1964) citing abundant analytical information for nickel in the lateritic soils and underlying peridotites near Democrat and at other well-known peridotite localities in the southeastern United States.

ANALYTICAL PROCEDURES

Two analytical procedures employed in this investigation are similar to those described by Bloom (1962) and Hill and Ellington (1961). In the "total" nickel procedure, the sample is digested in a nitric acid solution, and virtually all the nickel is extracted. The other procedure is based on partial extraction of nickel by a buffered ammonium citrate solution, and is referred to as the "available" nickel procedure. Both procedures utilize dimethylglyoxime which reacts with nickel to form nickeliferous dimethylglyoxime. The latter is subsequently extracted with isoamyl alcohol. Comparison of the color of the extracted phase with those of standards permits the estimation of the nickel content over a range of 25 to more than 10,000 ppm nickel. According to experiments by Bloom (1962), color interferences are not produced by copper or cobalt when the amount of either element is less than 500 micrograms. However, when 200 micrograms of each metal are present in a solution containing 12 micrograms of nickel, an anomalous yellow color is produced. Bloom (1962) notes that the anomalous color is eliminated by addition of hydroxylamine hydrochloride.

In the present study, the procedure of Bloom (1962) was followed with the exception of the following modifications.

Isoamyl alcohol is employed as an extractant instead of xylene because it enables detection of lower concentrations of nickel in standards. Moreover, our experiments indicate that a mixture of xylene and isoamyl alcohol, proposed as an extractant by Brotzen and Obial (1963) is less satisfactory than isoamyl alcohol alone. Hill and Ellington (1961) prescribe the use of isoamyl alcohol in their procedure.

Bloom (1962) recommends the addition of a special detergent, butyl phenoxy polyoxethylene ethanol (commercially known as "Aquet"), to a xylene extractant to retard the precipitation of nickel and facilitate colorimetric comparisons with standards. Precipitation of nickel does not present a serious problem when isoamyl alcohol is employed. Hence, the detergent was not utilized in the present study.

Another modification is the use of denatured alcohol (Rexall brand, 70 percent ethyl alcohol) as a solvent for dimethylglyoxime rather than absolute ethyl alcohol prescribed by Bloom (1962). Experiments indicate that lower concentrations of nickel are detectable in

standards when denatured alcohol is the solvent. Nickel contamination was not detected in the denatured alcohol. The reason for the increased sensitivity was not investigated.

In the "available" nickel procedure, an abundance of suspended matter in the extracted phase is a major source of error because the lack of clarity prevents accurate color comparisons with the standards. For this reason a centrifuge was utilized to separate clay-size particles from the organic layer. This technique greatly enhances the reliability of color comparisons.

REGIONAL GEOLOGY

The distribution of ultramafic rocks in western North Carolina and the location of the study area are shown in Figure 1. Peridotites[1] are the most abundant type and they are comprised mainly of dunite. Complex peridotites also contain saxonite and pyroxenite. Serpentine, talc, anthophyllite, and chlorite are common hydrothermal alteration products. The peridotites have intruded gneisses and schists which Keith (1904, 1905) mapped as Carolina Gneiss and Roan Gneiss. Radiometric age determinations indicate a Precambrian age for the country rocks. Locally, pegmatites and alaskite have intruded the peridotites. According to radiometric age determinations in the Spruce Pine district by Kulp and Eckelmann (1961), the pegmatites were emplaced about 350 million years ago. Recently, Conrad et al (1963) have suggested a Precambrian age for the peridotites, while Stuckey (1965) indicates that they are probably Ordovician in age and were emplaced during Taconic orogeny. Parker (1952) and King (1955) consider the peridotites to be of Paleozoic age.

GEOCHEMICAL STUDY

The two peridotites in the Democrat area are shown in Figure 2. Hunter (1941) refers to the southernmost peridotite as the Democrat deposit and the one to the north as the Holcombe Branch deposit. The country rocks (not designated on map) include biotite-hornblende gneiss and feldspar-mica gneiss (Roan Gneiss and Carolina Gneiss of Keith, 1904, 1905).

A series of soil samples was collected at a depth of approximately 12 inches from the Democrat deposit along a roadcut that transects the western portion of the deposit (Figure 2). The concentrations

1. The term peridotite, in this paper, refers to plutonic rocks containing olivine but little or no feldspar.

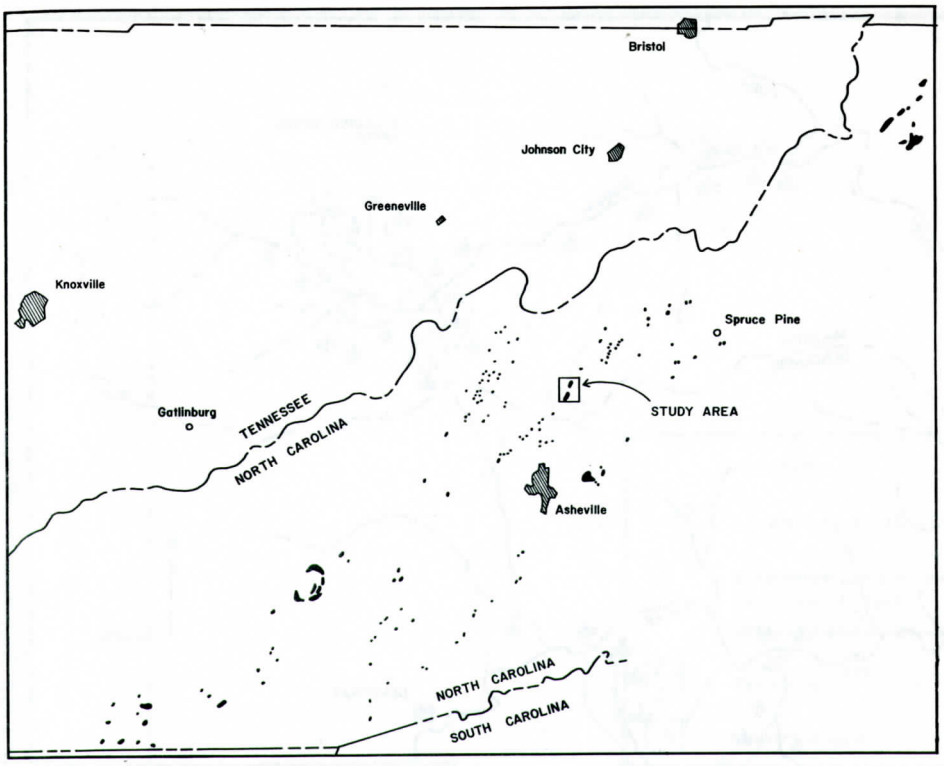

Figure 1. Map showing the distribution of ultramafic rocks in western North Carolina and the location of the study area. The geology is adapted from King (1955).

of nickel in the samples determined by the "total" nickel and "available" nickel procedures are presented in Figure 3. In these samples, the soil overlying peridotite contains over 900 ppm nickel, whereas soils developed on the country rocks generally contain less than 25 ppm nickel. The "available" nickel content is much lower, but clearly distinguishes the residuum derived from the peridotite from soil overlying the country rocks which consist of mica schists and gneisses.

Concentrations of nickel determined for stream sediment samples are shown in Figure 2. "Total" nickel background values indicated by those samples taken upstream from the Holcombe Branch and Democrat deposits are less than 25 parts per million.

The Democrat deposit is drained by several small tributaries of Ivy Creek. "Total" nickel values reveal anomalous concentrations of nickel in stream sediments as much as 4,000 feet downstream from the deposit. Ivy Creek is a major stream in the area and transects the northern tip of the Democrat deposit. A sample taken from Ivy Creek

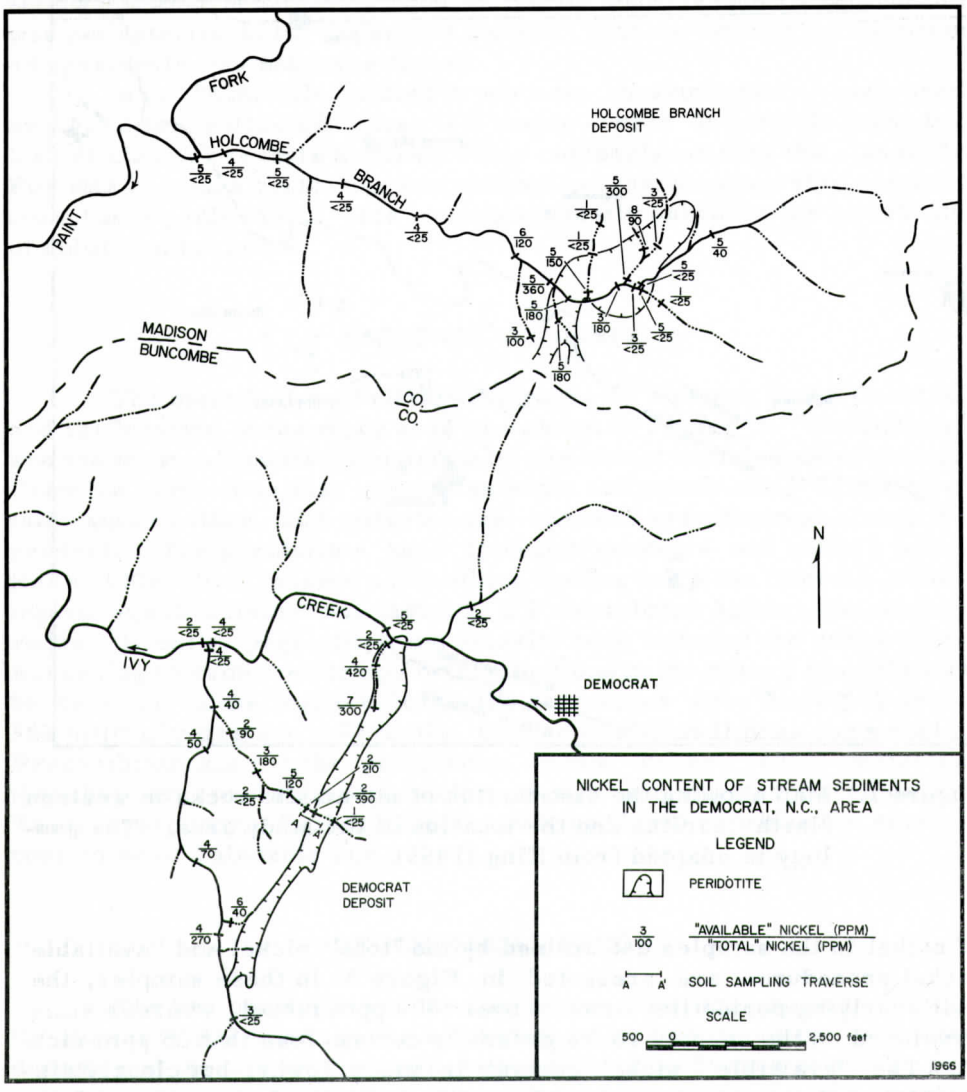

Figure 2. Map showing the distribution of peridotites and the nickel content of stream sediments in the vicinity of Democrat, North Carolina. The location of the soil sample traverse is indicated by the line A-A'. The outlines of the peridotites are taken from a report by Hunter, Broadhurst, and Robinson (written communication, 1940).

downstream from the peridotite is not anomalous.

Values cited for "available" nickel are very low and show poor correlation with the total nickel values. Downstream dispersion of nickel is essentially undetectable using the "available" nickel procedure.

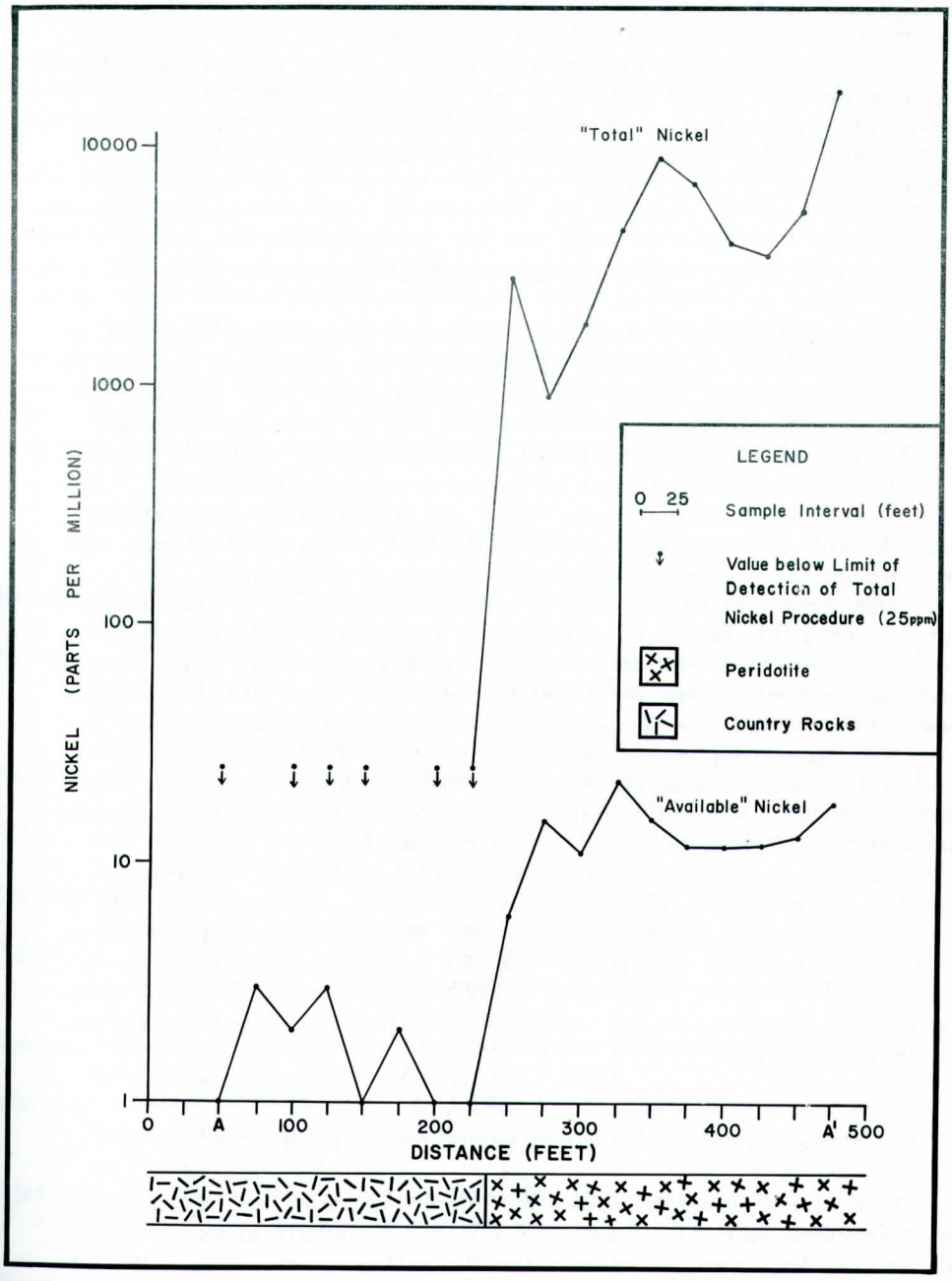

Figure 3. Diagram showing the "available" and "total" nickel concentration of soil samples collected on, and adjacent to, the Democrat deposit. The samples were collected along the traverse line A-A' shown in Figure 2.

This suggests that nickel occurs mainly in discrete mineral grains rather than ions adsorbed on mineral particles.

Anomalous stream sediments along Holcombe Branch extend to some point between 1,000 and 2,700 feet downstream from the western boundary of the peridotite. The relationship between "available" and "total" nickel values is virtually identical with that determined for the Democrat deposit.

APPLICABILITY OF GEOCHEMICAL PROSPECTING

The poorly defined dispersion patterns indicated by the "available" nickel content of stream sediments in the vicinity of two peridotites near Democrat, North Carolina, suggest that this method has little or no applicability as an exploration tool in the search for lateritic nickel deposits in the Blue Ridge. However, the "available" nickel detectable in soil samples may be useful in mapping peridotites. If a one gram sample contains more than six micrograms of "available" nickel, the soil is probably residuum derived from peridotite. The time required for a single analysis is only about one minute.

The "total" nickel content of stream sediments provides a satisfactory exploration tool if the spacing of samples along a stream does not exceed 2,000 to 3,000 feet. As large streams may not contain anomalous concentrations of nickel in sediments even though the sediments are only a few feet downstream from peridotite exposures in the stream bed, sampling should be chiefly in minor tributaries. In addition to nickel, this procedure is potentially applicable to the exploration for other minerals associated with peridotites, i.e., olivine, chromite, anthophyllite asbestos, corundum, and vermiculite.

Another application of the "total" nickel method is in preliminary evaluation of a known nickel deposit. Fairly accurate analyses of augered soil samples can be made in the field if the sample solution aliquots are carefully measured and if a balance is utilized in determining sample weights. Normally, more than 50 analyses can be made per man-day depending on the efficiency of the analyst and the degree of accuracy required.

EXPLORATION FOR LATERITIC NICKEL DEPOSITS

In a recent paper Worthington (1964) concludes that some of the basic requirements for a potentially minable lateritic nickel ore body exist for certain known deposits in the Blue Ridge area. These include (1) nickeliferous ultramafic rocks with a minimum surface area of approximately one square mile, (2) accumulation of lateritic soils averaging 25 feet or more in thickness, and (3) an average grade of about 1 percent nickel. However, no single deposit examined by Worthington

(1964) was found to meet all three of these requirements.

The desirability of continued exploration for nickel in the Blue Ridge area depends on the likelihood of discovering additional large ultramafic intrusives. Geochemical prospecting provides a satisfactory tool for locating and delineating such bodies.

Detailed mapping comprises less than 15 percent of the ultramafic belt in western North Carolina and Georgia. Most of the known ultramafic intrusives were discovered in the late 1800's during the period of active corundum mining and are described by Pratt and Lewis (1905). In recent years, additional occurrences have been discovered in those areas where detailed geologic mapping has been undertaken. An example is the area around Chatuge Reservoir in Towns County, Georgia, and Clay County, North Carolina, where only two peridotites were known prior to detailed mapping by TVA geologists in 1941 and 1942. Six additional peridotites were discovered , three of which exceed one square mile in area (personal communication, J. M. Kellberg).

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REDEFINITION OF THE HILLABEE SCHIST, ALABAMA

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ABSTRACT

Field studies, supported by microscopic, X-ray and chemical analyses, show that the Hillabee Schist may be subdivided into rocks which represent an altered, basic igneous intrusion, and altered metasediments of the adjacent Talladega and Ashland Groups. It is suggested that "Hillabee Sole Injection" be used to designate the basic igneous rocks within the green schist belt and that the altered metasediments be designated properly as altered facies of the Talladega and Ashland Groups.

The Hillabee Sole Injection is characterized mineralogically by a preponderance of hydrous ferro-magnesian minerals plus plagioclase feldspar and chemically by relatively low silica and relatively high calcium, magnesium, and iron contents. The altered facies of the Talladega and Ashland Groups are characterized mineralogically by a preponderance of quartz plus minor quantities of feldspar and hydrous ferro-magnesian minerals and chemically by a relatively high silica and relatively low calcium, magnesium and iron contents. Textural differences also serve to aid the distinction of the subdivisions.

INTRODUCTION

Geologic Setting

The Ashland Plateau, the mountainous part of the Alabama Piedmont Province (Adams, 1926), may be roughly divided into two parts. The northwestern part is underlain by low-rank metasediments of the Talladega Group; the southeastern part is underlain by relatively higher-rank metasediments of the Ashland Group and intrusive igneous rocks (Figure 1). The boundary between the two parts is marked by the trace of the Whitestone fault, a major thrust along which the Ashland Group was displaced northwestward onto the younger Talladega Group. The Hillabee Schist, a belt of chlorite, epidote and/or amphibole-rich

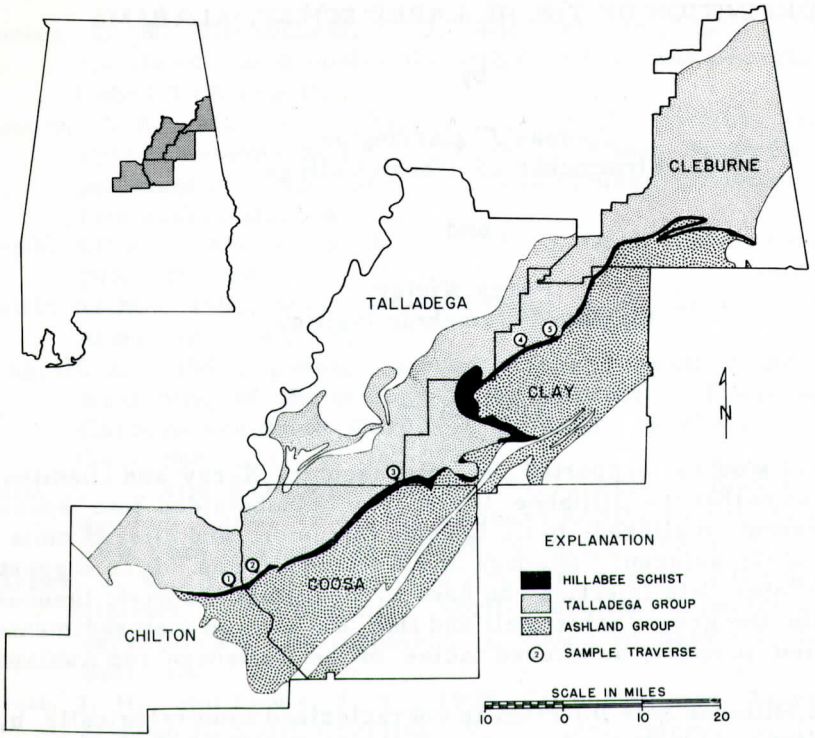

Figure 1. Outcrop geology of Hillabee Schist of Smith and related rocks. At the indicated sample traverse locations, the thicknesses of the "Hillabee Schist", as previously mapped, are: (1) 530 feet, (2) 1200 feet, (3) 1580 feet, (4) 500 feet, and (5) 575 feet.

schists in which there has been sporadic interest for many years because of its content of pyrite, copper, and/or gold, is locally conterminous with the trace of the Whitestone fault.

Regional geologic structures within the areas underlain by the Talladega and Ashland Groups and the general trend of the Whitestone fault are parallel to major Appalachian structural trends of the region. Regional dips of the rocks and of the fault are to the southeast.

History of Investigation

Phillips (1892) noted the occurrence of similar green schists in the vicinities of Millerville, Iwana, and Hillabee, Alabama. Brewer (1896), using the names of Phillips' localities where the characteristic rocks crop out, applied the names "Millerville", "Iwana," and "Hillabee" Schist to what was later mapped (Prouty, 1922; Adams, 1926; Griffin, 1951; Baker, 1957; and Clarke, 1963) as an almost continuous

belt of green schists that occupy a northeastwardly striking belt more than one hundred miles long. These green schists generally form the southeastern boundary of the Talladega Group. Smith (1896) included the rocks of all three "type" areas under the name "Hillabee Schist", suggested a similar origin for all the rocks so included, and noted both the igneous and sedimentary features of the rocks. Griffin (1951) referred to the "Hillabee Sill", although on his map he showed structural trends within the Hillabee Schist to be different from those in the Talladega Group and the Ashland Group. Baker (1957) also designated the Hillabee as a sill.

The Hillabee Schist is thought by most workers to have been of igneous origin, but opinions are diverse as to the type of igneous activity represented. Some (Clements and Brooks, 1896; Prouty, 1923; Adams, 1926; Griffin, 1951; and Baker, 1957) favor an igneous intrusion of basic composition along the Whitestone fault prior to regional metamorphism. In addition, Prouty (1923) suggested movement along the fault following intrusion. Griffin (1951) distinguished silicic central and mafic border phases. On the other hand, an extrusive origin is suggested by Smith (1896) and Shaw (1963, personal communication). Clarke (1963, 1964), who favors an origin involving alteration of marine shales which perhaps contained volcanic ash and/or basic lava flows by processes of hydrothermal, metasomatic, or other altering agencies, notes that rocks of the Talladega Group may be traced with increasing degree of alteration into rock mapped as Hillabee Schist.

The study reported on in this paper provides evidence for the recognition, within the Hillabee Schist as previously mapped, of three units which probably represent sheared, hydrothermally altered, and metamorphosed basic igneous intrusive rocks which are locally flanked by similarly altered metasediments of the Talladega and Ashland Groups. The intrusion was along the Whitestone fault. Thus it is suggested that the designation, "Hillabee Sole Injection", be used for the rocks within the green schist belt which have an igneous origin and that the adjacent altered metasedimentary rocks be reassigned to their proper places and be called altered facies of the Talladega and Ashland Groups.

Location and Purpose of Study

Descriptions of outcrops and samples of the formerly designated Hillabee Schist along five tape and compass traverses between Pyriton, Clay County, and U. S. Interstate 65, Chilton County, Alabama (Figure 1), have been prepared as part of a National Science Foundation sponsored, Undergraduate Research Participation Program at Birmingham-Southern College. During the summer of 1963, the traverses were extended from rocks of the Ashland Group generally northwestward across the outcrop belt of the Hillabee Schist into rocks of the Talladega Group. Laboratory work involving microscopic, X-ray, and chemical analysis of samples was done between the fall of 1964, and the spring of 1966.

Acknowledgments

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DESCRIPTION OF ROCK TYPES

Ashland Group

The rocks of the Ashland Group have been generally regarded as Precambrian in age (Prouty, 1923; Adams, 1926; Hunter, 1944; and Griffin, 1951) although at least some of the rocks within the group may be Paleozoic in age (Deininger, 1964). The rocks, which in this area are predominantly of the almandine amphibolite regional metamorphic facies, are comprised by a variety of metasedimentary and metaigneous rocks, among which are phyllite, mica schist (locally containing garnet, kyanite, or hornblende), granulite, gneiss, amphibolite, and quartzite. Many of the lithologies are cut by pegmatities, aplite, and/or quartz veins.

Although the lithologic sequence within the Ashland Group is not known, many lithologic units (undefined formations) may be traced for many miles along strike. Thus, the Ashland should be designated as a group. The thickness of the group is estimated to be more than 10,000 feet (Adams, 1926).

Talladega Group

The name, "Talladega Group", was applied by Smith (1888) to a thick sequence of low grade metamorphosed sedimentary rocks exposed along Talladega Creek, Talladega County, Alabama. "Talladega Slate", "Talladega Phyllite", and "Talladega Series" are other names which have been applied to all or part of the sequence (e.g., Prouty, 1923; Butts, 1926; Baker, 1957; Carrington, 1964; and Carrington and others, 1964).

Slate and arkosic quartzite comprise most of the sequence, but limestone, calcareous sandstone, marble, conglomeratic graywacke, and chert comprise significant as well as distinctive units within the group. Butts (1940) divided the Talladega Group into three formations, each of which is thousands of feet thick, and which are in ascending order: Waxahatchee Slate, Brewer Phyllite, and Wash Creek Slate. Members, each of which is several hundred feet thick, are distinguished within the Waxahatchee (e.g., Sawyer Limestone) and Wash Creek (e.g., Jumbo Dolomite, Butting Ram Sandstone, Cheaha Sandstone, Jemison Chert, and Yellow Leaf Quartz Schist).

Commonly the schistosity, the amount and grain size of muscovite, and the abundance of quartz in veins and pods is noticeably greater in pelitic rocks of the Talladega Group nearer the Whitestone fault and/or "Hillabee Schist".

The thickness of the Talladega Group ranges from 11,000 to 28,000 feet. Details of structure remain to be worked out, however, so the thicknesses may be considerably less than indicated because of repetition by folding and faulting.

The general consensus is that the Talladega Group includes metasediments that range in age from Cambrian to Carboniferous.

Hillabee Schist of Smith

General. As previously mapped, the "Hillabee Schist" underlies a generally southwestwardly trending valley or belt of valleys, the width of which depend upon the thickness and structure of the underlying rocks and the lithologies and structures of the adjacent rocks of the Ashland and Talladega Groups.

The thickness of the "unit" ranges from about 500 to 1600 feet in the areas traversed during this investigation (Figure 1). According to Butts (1926) and Griffin (1951), in some localities not traversed in this study, the "unit" is absent along the Whitestone fault; at some unmeasured localities its thickness may be greater than the indicated maximum.

In fresh exposures the Hillabee Schist is a gray-green, fine-grained rock in which foliation is defined by alternating, thin (less than 5mm), irregular laminae of white to cream-colored feldspar and/or quartz, and of medium to dark green chlorite, amphibole, and/or epidote. Commonly there is a shear foliation that intersects the compositional foliation at an acute angle. Locally, irregularly discontinuous veins or pods of quartz, oriented parallel or sub-parallel to the compositional foliation, are present. The veins, which range from a few millimeters to about 40 cm thick, are folded, fractured, and faulted. This indicates their formation to have occurred prior to the latest deformation of the Hillabee. Irregular masses of rock identifiable as typical of the Talladega or Ashland Groups occur sporadically within the belt of rocks mapped as Hillabee Schist. These masses range up to 300

feet long by 50 feet across and, in general, are oriented with their long axes, and less commonly their foliation, parallel or subparallel to the trend of the foliation in the enclosing rocks.

The Hillabee Schist typically weathers rusty yellow-brown, but locally weathers black along joint surfaces which transect foliation. The soil derived from the "unit" is a deep yellow to dark brown-red, cohesive clay or quartzose clay which in many respects resembles soils derived from weathering of carbonate sedimentary rocks within the region.

The strike of foliation within the Hillabee Schist ranges greatly, but in the localities traversed during this study the strike ranges from N 43° E to N 78° E, with most about N 60° E. The dip is to the southeast and typically is about 30-35 degrees.

The age of the Hillabee Schist is thought to be post-Carboniferous and pre-Upper Cretaceous (Adams, 1926 and Griffin, 1951).

Hillabee Sole Injection. The Hillabee Sole Injection makes up as much as one-half the thickness of the Hillabee Schist as previously mapped, but typically comprises less than one-third. Rocks of the sole injection are now made up almost entirely by assemblages of minerals that have resulted from metamorphism and hydrothermal alteration of the original rocks. Lithologically, the sole injection is characterized by laminae of predominantly dark minerals alternating with laminae of predominantly light minerals. Typically the laminae are irregular and discontinuous and are less than 2mm thick. Incipient cleavage is generally present in two planes that intersect each other at about 80 degrees: for instance, one about 35 degrees from the compositional foliation and the other at about 45 degrees in the opposite direction from compositional foliation.

The rocks of the Hillabee Sole Injection exhibit evidence of advanced cataclasis. Flaser comprised by aggregates of anhedral feldspar occur sporadically within a slightly foliated groundmass consisting chiefly of secondary minerals and scattered, angular fragments of feldspar. Rotation during cataclasis is suggested by the sigmoidal shapes of many flaser. The flaser range up to a millimeter in width and several millimeters long, whereas grains of the groundmass range from about 0.01 mm to 0.5 mm in greatest dimension.

Most rocks of the sole injection are characterized by significant amounts of chlorite, epidote, amphibole and andesine-oligoclase feldspar, and the absence or near absence of quartz (Table 1). The actual mineral content ranges widely, both through the thickness of the sole injection and along strike: for examples, epidote, chlorite and/or amphibole range from 52 to 74 percent; plagioclase ranges from 26 to 44 percent; and grossularite, ilmenite, leucoxene, sphene, pyrite, or other accessories range up to 5 percent.

Epidote is colorless to slightly greenish yellow, pleochroic, and occurs as subhedral to anhedral grains which range from 0.02mm to 0.25mm across. Locally the foliation appears to have been pushed

Table 1. Comparison of Partial Mineral Compositions in Percent.

	T-1	AT-2	SI-3	SI-4	SI-5	SI-6	SI-7	AA-8	A-9
Quartz	53.0	72.0	46.0					52.0	20.0
Muscovite-sericite	45.0	25.0	2.0						64.0
Chlorite-epidote-amphibole		3.0	21.0	73.0	67.0	74.0	51.0	6.0	2.0
Plagioclase			13.0	23.0	32.0	26.0	44.0	11.0	12.0

T-1. Unaltered quartz-sericite schist, Talladega Group, Clay county, Alabama
AT-2. Altered facies, Talladega Group, Clay County, Alabama
SI-3. Hillabee Sole Injection, Clay County, Alabama
SI-4. Hillabee Sole Injection, Clay County, Alabama
SI-5. Hillabee Sole Injection, Clay County, Alabama
SI-6. Hillabee Sole Injection, Clay County, Alabama
SI-7. Hillabee Sole Injection, Clay County, Alabama
AA-8. Altered facies, Ashland Group, Clay County, Alabama
A-9. Unaltered Ashland Group, (garnetiferous, quartz-feldspar-mica schist), Clay County, Alabama

aside by larger grains, some of which are in part discordant to the foliation. Such grains may be porphyroblasts of an earlier generation than the smaller, more abundant grains, or more likely they may be replacements of plagioclase (several grains preserve polysynthetic twinning of the replaced plagioclase). Most of the epidote, however, may have been derived from alteration of hornblende because within given sample areas the amount of hornblende ranges indirectly with the epidote content, whereas the plagioclase content is relatively constant.

Chlorite occurs as irregular aggregates of sub-parallel flakes scattered through the groundmass and as aggregates concentrated around plagioclase grains, with which it is most commonly associated. Apparently most of the chlorite formed in low pressure areas during metamorphism because it is concentrated at the ends of plagioclase grains along foliation, and only constitutes a thin zone around the remainder of the plagioclase grains. Locally the plagioclase and associated chlorite are enclosed within aggregates of actinolite grains. The chlorite is optically positive penninite which is pleochroic (with X= light yellow, Y= deep green, and Z= light yellow). The grains are typically less than 0.5mm across.

In given sample areas amphibole occurs in different combinations of relict hornblende, pargasite, and/or actinolite-tremolite. Relict hornblende is pleochroic from light yellow-green to medium green, locally includes apatite, and shows incipient alteration to chlorite and/or actinolite. Grains are as large as 0.5mm x 2mm and are present as aggregates or as scattered, individual grains. Pargasite occurs as grains associated with or enclosed within plagioclase and is pleochroic from clear (or light yellow) to light green. Grains average 0.03 x

0.1mm. Actinolite-tremolite occurs as minute laths (0.01 x 0.1mm) that are oriented sub-parallel to foliation and apparently formed by alteration of relict hornblende. In rocks containing relict hornblende, tremolite-actinolite is a common associate. Actinolite is pleochroic from light yellow to light green, and is more common than tremolite in rocks of high iron content, such as the pyritiferous representatives at Pyriton, Clay County, Alabama.

Plagioclase (An_{28-33}) occurs as subhedral to anhedral, generally untwinned grains which are typically fragmented and partially altered to sericite and/or epidote. Small laths of pargasite(?) or actinolite-tremolite(?) are typically enclosed within plagioclase grains. Plagioclase ranges from about 0.01mm to more than 1.5mm across, and occurs as single grains scattered through the dark-mineral layers, as aggregates of interlocked grains forming feldspar-rich layers, and as aggregates of grains constituting flaser.

Sphene (typically rimmed with leucoxene) occurs locally as euhedral to subhedral, unoriented grains which range up to 0.1mm across, commonly in association with chlorite and epidote. Ilmenite(?) occurs sporadically as leucoxene-rimmed grains up to 0.1mm across. Pyrite is present as euhedral grains which are up to 5mm across. Grains are typically unoriented, displace adjacent folia, and are poikiloblastic with included plagioclase. Pyrite grains are typically partially altered to iron oxide. Prehnite with characteristic sheaf structure occurs sparsely.

Garnet is of two sizes: relatively large (to 0.25mm), anhedral grains and smaller (to 0.01mm) dodecahedra. Both are somewhat anisotropic. Their association with epidote and altered plagioclase, their anisotropism, and their clear white color in thin-section suggest they are probably grossularite. The larger grains occur sporadically, whereas the smaller grains occur in "swarms".

The chemical compositions of all samples of the Hillabee Sole Injection are similar to the compositions of the igneous rocks shown in Columns 10, 11, and 12 (Table 2), particularly to those of the hornblende gabbro (10) and olivine-free diabase (11). The contradictory results of mineralogical and chemical analyses of Sample 3 (Tables 1 and 2) suggest that the rock may represent a differentiate or an incompletely assimilated or altered mass of wallrock.

Altered Metasedimentary Facies. Mineralogically the altered facies of the Talladega and the Ashland Groups, which flank the Hillabee Sole Injection, respectively, to the northwest and southeast, and which have in the past been mapped as part of the "Hillabee Schist", are similar in that quartz is their major constituent (Table 1). Chlorite, epidote, and amphibole in various combinations and plagioclase are present, but do not constitute a significant portion of the rock. Muscovite (sericite in the altered facies of the Talladega Group) locally comprises a large proportion of the rock, but is not omnipresent within the facies.

Table 2. Comparison of Partial Chemical Compositions in Percent.

	T-1	AT-2	SI-3	SI-4	SI-5	SI-6	SI-7	AA-8	A-9	G-10	D-11	D-12
SiO_2	89.0	88.9	52.9	41.7	53.5	54.9	52.4	77.7	63.0	52.2	52.9	52.3
Al_2O_3	6.8	7.0	17.2	20.1	11.1	10.1	11.4	12.2	20.4	11.7	14.1	13.7
Fe_2O_3 FeO	1.7	1.5	9.9	10.5	10.2	6.4	12.6	3.2	4.3	10.8	12.2	13.8
MgO	0.4	---	3.8	6.8	7.2	11.0	8.9	1.3	2.2	9.8	3.6	4.7
CaO	0.4	---	5.5	9.4	14.2	14.3	7.0	1.7	1.1	9.4	8.2	8.0
Na_2O	---	---	7.0	8.0	2.2	2.4	2.3	1.2	2.9	1.9	2.6	2.6
K_2O	---	2.0	---	---	---	---	---	1.2	1.6	---	---	---

T-1. Unaltered Quartz-sericite schist, Talladega Group, Clay County, Alabama
AT-2. Altered facies, Talladega Group, Clay County, Alabama
SI-3. Hillabee Sole Injection, Clay County, Alabama
SI-4. Hillabee Sole Injection, Clay County, Alabama
SI-5. Hillabee Sole Injection, Clay County, Alabama
SI-6. Hillabee Sole Injection, Clay County, Alabama
SI-7. Hillabee Sole Injection, Clay County, Alabama
AA-8. Altered facies, Ashland Group , Clay County, Alabama
A-9. Unaltered Ashland Group, (Garnetiferous, quartz-feldspar-mica schist), Clay County, Alabama
G-10. Hornblende gabbro, Johannsen, v. 3, 1937, p. 220.
D-11. Olivine-free diabase, Johannsen, v. 3, 1937, p. 315.
D-12. Quartz diabase, Daly, 1933, p. 18.
(Samples 1, 3, 4, 8, and 9 chemically analyzed by James C. Lloyd, Alabama Testing Laboratories, Birmingham, Alabama; samples 2, 5, 6, and 7 calculated from microscopic mineralogical analyses).

The altered facies of the Talladega and Ashland Groups are also similar chemically in that the silica content of the rocks is characteristically greater than 75 percent (Table 2), and the silica plus alumina content is typically in excess of 89 percent, both higher than those characteristic of rocks of the Hillabee Sole Injection.

The altered metasedimentary facies may be distinguished from each other, as well as from the Hillabee Sole Injection, where relict texture is recognizable. Schistose and gneissose textures, particularly where relict garnet (almandite) is present, serve to distinguish the altered facies of the Ashland Group from the generally much finer grained rocks of the altered facies of the Talladega Group. Less altered samples of the metasedimentary rocks typically exhibit laterally persistent compositional and/or textural lamination, in contrast to the commonly irregular and lensoid character of the "laminae" in the more highly altered metasedimentary and meta-igneous rocks. Weathered specimens of altered metasedimentary rocks typically exhibit quartz grains in a groundmass of iron-oxide stained, clayey material. It appears, although not conclusively proved, that the quartz veins or pods mentioned in the general description of the "Hillabee Schist" are restricted to the altered facies of the Ashland Group.

Gradation from altered facies of metasedimentary rocks into progressively less altered metasedimentary rocks is megascopically demonstrable. Definition of the contacts between the altered facies of the metasedimentary sequences and the Hillabee Sole Injection are not sufficiently distinct for megascopic definition.

Altered Facies of the Ashland Group. Most of the altered facies of the Ashland Group is chlorite-epidote-feldspar-quartz schist. Some of the sample localities, however, also contain rocks which are comprised by significant amounts of carbonate minerals. The texture is characteristically fine to medium grained, and "layers" of light colored minerals (quartz, muscovite, feldspar, and/or carbonate) and dark colored minerals (chlorite, epidote, actinolite-tremolite, and/or iron oxide) alternate. The "layers" are irregular to lensoidal, and commonly are transected by secondary cleavage, so that there are few good planes of schistosity.

In general the mineral percentages are as follows: quartz, 25-45; muscovite (and/or sericite), 0-45; almandite garnet, 0-12; epidote, chlorite, and/or actinolite-tremolite, 0-50; and plagioclase, 0-15.

Quartz is present as anhedral grains that are clear and typically strained. Grains are scattered sporadically in ill defined zones or are present as aggregates which define compositional zones relatively well. Grain sizes range up to 1.0mm across.

Muscovite (or sericite) occurs as felty, sub-parallel aggregates of locally iron-stained flakes, the individual grains of which range up to 3.0 mm in length. Secondary shear planes and micro-folding typically distort the aggregates.

Garnet (almandite) is typically subhedral and poikiloblastic with inclusions of quartz, mica, feldspar, and rounded zircon. Alteration to iron oxide is common.

Epidote, chlorite and actinolite-tremolite are essentially as described for those minerals in the Hillabee Sole Injection.

Plagioclase (typically An_{28}, but rarely as low as An_{14}) is present as anhedral, commonly untwinned grains which range from 0.05mm to 0.5mm in greatest dimension. Grains, which are scattered unevenly through the groundmass, are typically sericitized and associated with epidote.

Calcite and/or dolomite locally comprise the predominant part of the light colored layers. Grains are typically twinned and occur in unoriented, interlocking aggregates.

Quartz grains which are common as inclusions are subrounded to rounded.

Altered Facies of the Talladega Group. The altered facies of the Talladega Group is represented by chlorite-epidote-feldspar-quartz schists that are typically fine grained and locally garnetiferous. Schistosity is poorly defined in the more highly altered rocks by irregular to lensoidal aggregates of light colored minerals (quartz, sericite, and locally feldspar) alternating with dark colored minerals (chlorite, epi-

dote, and locally amphibole or iron oxide).

The mineral percentages are as follows: quartz, 39-72; epidote, chlorite and/or amphibole, 21-52; sericite, 2-25; and plagioclase, 0-13.

Quartz occurs similarly to that in the altered rocks of the Ashland Group, but is more abundant and finer grained (up to 0.2mm across). Minute laths of sericite(?) are common as unoriented inclusions within the quartz.

Plagioclase (typically An_{28}, but rarely as low as An_{14}) and combinations of chlorite-epidote (and locally tremolite-actinolite) also occur similarly to those in the altered facies of the Ashland Group.

Sericite occurs as minute (less than 0.1mm long) laths enclosed within quartz grains, and as long, irregular stringers of aggregated flakes which locally are distorted by secondary shearing and microfolding. The sericite is typically iron-stained and locally replaced by chlorite.

Traces of grossularite garnet which occur locally are similar to those in the Hillabee Sole Injection. Traces of clinozoisite, zircon, ilmenite, pyrite, apatite, and sphene also occur.

CONCLUSIONS

Mineralogical, chemical, and structural evidence suggest that the "Hillabee Schist" as previously mapped as a sill may be divided into metamorphosed and hydrothermally altered rocks which represent (1) an originally basic igneous mass intruded along the Whitestone fault, and similarly altered metasediments of the (2) Talladega and (3) Ashland Groups.

The rocks which lie within the green schist belt and which may be shown to have had an igneous origin prior to alteration are herein designated the "Hillabee Sole Injection". The similarly altered metasediments which flank the sole injection are renamed as altered facies of the Talladega and Ashland Groups.

Movement along the Whitestone fault subsequent to consolidation of the igneous intrusion caused granulation and probably local mylonitization of the rocks within and adjacent to the fault zone. Regional metamorphism with attendant hydrothermal activity in the later phases of metamorphism probably accompanied or followed the later movement along the fault. The granulated and disrupted rocks of the sole injection and adjacent metasediments were subjected to similar alteration by the metamorphic and hydrothermal agencies, but original differences in composition and/or texture between the igneous and metasedimentary rocks prevented the complete masking of their diverse origins.

There is no evidence in the areas of the present investigation that the Hillabee Sole Injection contains metamorphosed equivalents of a silicic central and mafic border phases, although one traverse of this

study (Traverse 3, Figure 1) crosses the "unit" where these phases have been previously mapped (Griffin, 1951, Geologic Map).

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A NORTH CAROLINA SHELF PHOSPHATE DEPOSIT OF POSSIBLE COMMERCIAL INTEREST

by

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ABSTRACT

An elongate, surficial deposit of phosphatic sand has been located adjacent to and east of Frying Pan Shoals off Cape Fear, North Carolina. The area of highest phosphate concentration is about 10 miles long and three to four miles wide and is in water depths between 20 to 30 meters. The richest sample obtained contained 40 percent phosphorite grains by count and 7.78 percent P_2O_5. Since the observed material is surficial the P_2O_5 values may have been decreased by dilution with quartz and shell material and increased by winnowing of non-phosphatic fines. Bottom photos and continuous bottom soundings indicate that rock outcrops are present. Dredged rocks from the area are friable, obviously weathering, slightly phosphatic limestones. It is tentatively concluded that the phosphatic sand is derived as a weathering concentrate from the outcropping limestone. It is suggested that the thickness of the deposit will depend on sub bottom topography and the length of time during which weathering of the limestone has occurred. Further prospecting of the area is definitely warranted. Suggested procedures for further investigation are given.

INTRODUCTION

With increasing demand for phosphate, it is not surprising that some interest has begun to focus on the continental shelf as a possible future source of phosphate. Studies by Stetson (1938), Gorsline (1963), Emery (1965), Luternauer (1966), Pratt and McFarlin (1966), Pevear and Pilkey (1966), and Luternauer and Pilkey (submitted) have demonstrated that high grade deposits of surficial nodules, such as those found off Southern California, are not present off the Southeastern United States. However, there is no reason to doubt that phosphatic sediments found in the exposed Atlantic Coastal Plain should be present in the submerged equivalent formations. For example the phosphate band on the inner Blake Plateau (Pratt and McFarlin, 1966) is most likely derived from Tertiary outcrops.

Luternauer (1966) recently completed an investigation of phosphorite distribution in North Carolina shelf sediments. The purpose of this study was to ascertain the value of phosphorite grains as a tool to aid in the understanding of shelf sediment transport. During the course of Luternauer's investigation a single sample containing an unusually large amount of phosphorite (33 percent by grain count) was noted from the vicinity of the Frying Pan Shoals off Cape Fear. In two subsequent cruises the area was investigated in detail.

Acknowledgments

The writers wish to thank the Duke University Marine Laboratory and the Duke University Oceanographic Program which is directed by Robert J. Menzies for the use of the R/V EASTWARD. The R/V EASTWARD is one aspect of the facilities of a co-operative research and training program in biological oceanography which is supported by NSF grant G-17669 to Duke University. The phosphatic sediment which is the subject of this report was discovered in the course of an investigation of carbonate sedimentation supported by NSF grant GP-4564 to O. H. Pilkey. Detailed investigation of the samples and the preparation of this report were supported by the North Carolina Board of Science and Technology. We wish to thank Barry W. Maynard and John Washburn for performing many of the analytical tasks required. Splendid co-operation was received from a number of commercial firms with phosphate interests, in analyzing our samples and agreeing to let us publish the data. In particular International Minerals and Chemical Corporation performed a large number of analyses. Compilation of and drafting of Figure 2 was accomplished by David Murphy under the supervision of John Newton, marine superintendent, Duke University Oceanographic Program.

METHODS

All sampling was accomplished from the R/V EASTWARD. Almost all samples were obtained by a small Pierce box dredge. No cores or geophysical sub-surface data were obtained. During one cruise a series of bottom photos were obtained using an Alpine multishot underwater camera.

A cut of each sample from the area in question was mounted on glass slides and phosphorite grains counted under the microscope. Identification of questionable grains was aided by the use of an acid ammonium molybdate stain. It should be emphasized that these are grain counts of total samples, not individual size fractions. P_2O_5 analyses were obtained from several commercial firms. Grain size, heavy mineral and percent insoluble residue data were obtained using standard techniques.

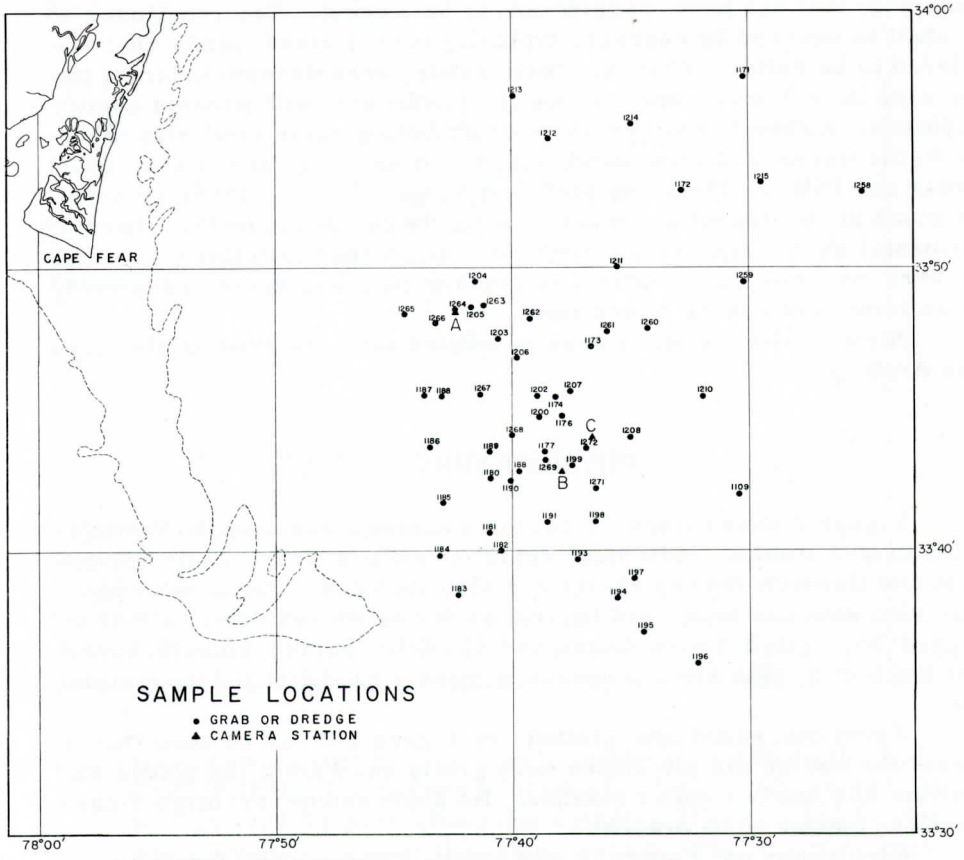

Figure 1. Map showing location of samples utilized in this investigation as well as Cape Fear and the outline of Frying Pan Shoals. The numbers are Duke University Geology Department sample collection designations. The letters next to triangle symbols designate camera station.

GEOLOGIC SETTING

The study area is located in the extreme southwest portion of Onslow Bay off the North Carolina coast. It is adjacent to Frying Pan Shoals off Cape Fear. Figure 1 shows sample locations.

The nature of shelf sediments in the study area is discussed by Stetson (1938), Gorsline (1963), Pilkey (1964), and Emery (1965). Several investigations on the nature of shelf sedimentation off North Carolina are presently being carried out by staff and students at Duke University as part of the Duke University co-operative oceanographic program.

Adjacent to the shoreline is a band of fine sand, often about 12 miles wide that has been considered to be Recent. The remainder of the shelf is covered by coarser, typically iron stained sands that are believed to be relict. That is, these sands were deposited during the last rise in sea level and are out of equilibrium with present energy conditions. Although rivers may be contributing some sand-size material to the Recent sediment band, there is mineralogical (Pilkey, 1963; Pevear and Pilkey, 1966) and sediment budget (Pierce, 1966) evidence that much of the Recent sediment is actually derived from the adjacent continental shelf. Apparently rock outcrops on the North Carolina shelf are very common, particularly in Onslow Bay and these undoubtedly are an important source of sediment.

Structurally the study area is located near the crest of the Cape Fear Arch.

PHYSIOGRAPHY

Figure 2 shows lines of bottom soundings based on R/V EASTWARD cruise tracks. Individual depth soundings from United States Coast and Geodetic Survey charts are also included. The area of phosphate rich sands is bracketed by, but as far as we can determine is not covered by, United States Coast and Geodetic Survey smooth sheets. Thus the bottom data are too sparse to make a good detailed topographic map.

From the soundings plotted on Figure 2 it can be seen that in general the bottom simply slopes very gently away from the shoals and coastline in a fairly regular manner. No depressions or large ridges or valleys appear to be present.

Also shown on Figure 2 are symbols designating the presence of ledges visible on R/V EASTWARD continuous sounding profiles. On the basis of the presence or absence of such ledges a large area of probable occurrence of outcrops is outlined by the solid line. The dashed line shows the location of richest phosphate sands. Note that the 15 mile wide outcrop area extends into and west of the phosphate deposit.

BOTTOM PHOTOS

Three bottom photo stations were occupied and between 20 and 30 photos were obtained at each. Bottom markings are generally subdued and indistinct. Animal trails predominate over ripple marks. Ripple marks when present are poorly developed and generally indicate weak current movement in a north-south direction. Several photos revealed a prolific "leafy" green algae growth on the bottom which most likely has a strong stabilizing effect on sediment movement.

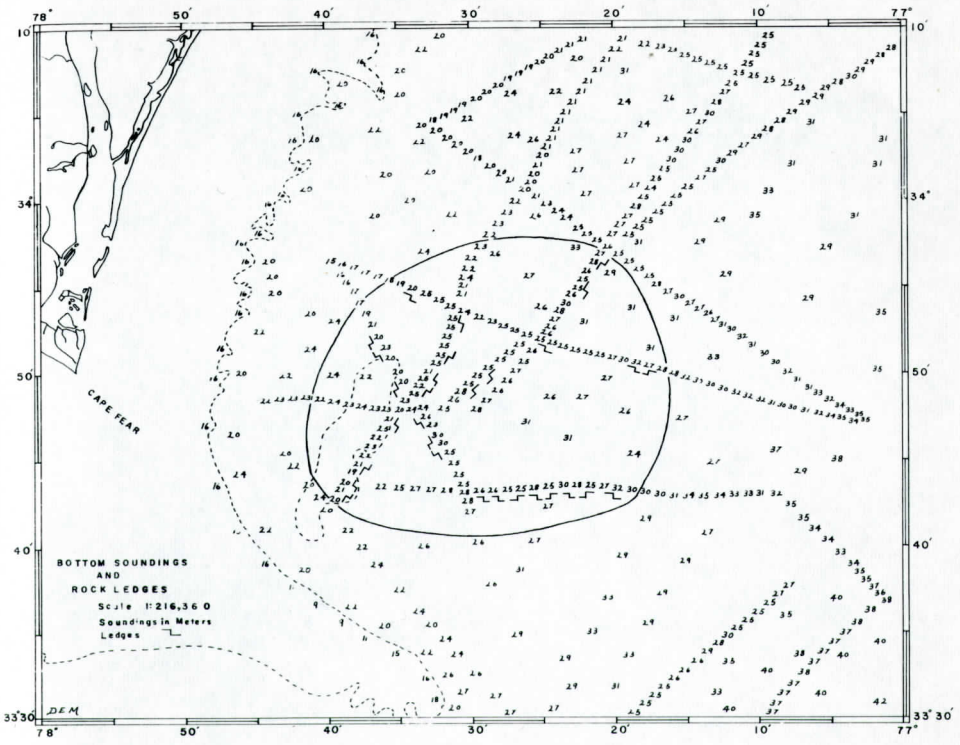

Figure 2. Map showing lines of bottom soundings made by the R/V EASTWARD. The presence of rock? ledges, large enough to be detected by precision echo sounding are designed by the small symbols along the ship tracks. The circled area shows the hypothesized extent of the area of numerous rock outcrops.

Figure 3 shows a rock ledge from station B. This is the only ledge photographed and it has a relief of about one meter. The rock is covered by prolific coral and algae growth, and judging from it's irregular shape, it may be the weathered, phosphatic limestone discussed below.

SEDIMENTS

Sediment types in the study area are highly variable and exhibit unusually rapid changes in various characteristics, particularly when compared with the rest of the Onslow Bay continental shelf. Rapid changes in bottom sediment type can also be spotted in bottom photos (see above). Because phosphorite is such an important sediment com-

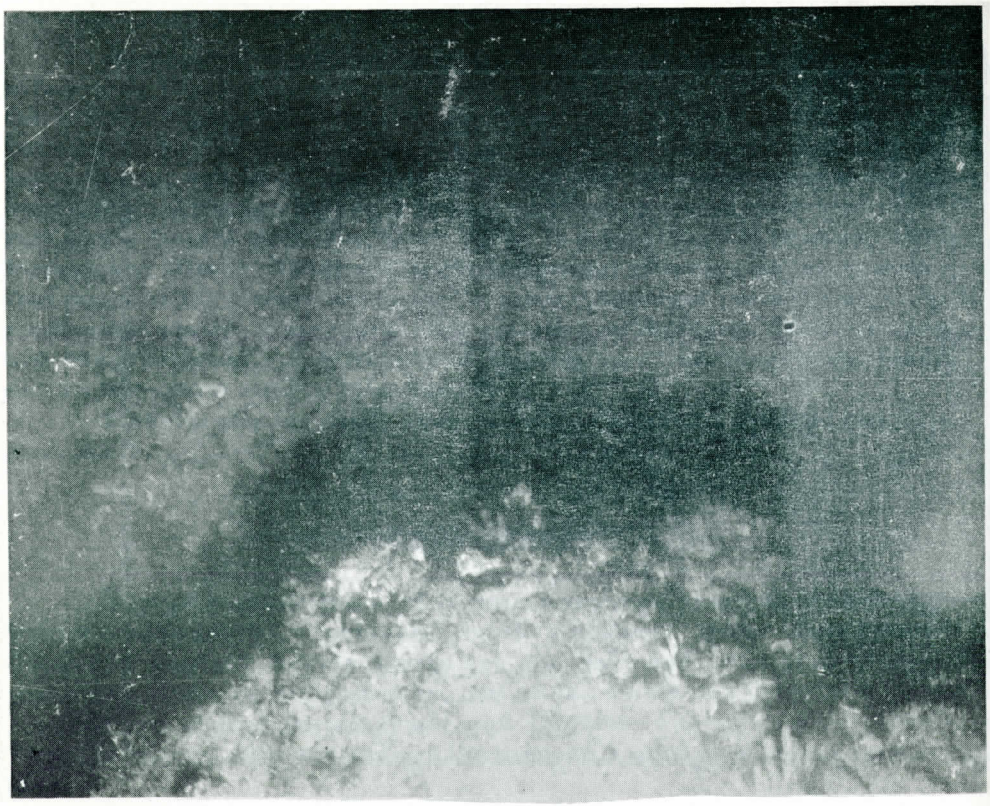

Figure 3. Bottom photograph from area B showing rock ledge. Area covered by photograph is about 2 meters wide at the base of the picture.

ponent, its abundance often controls the sediment color, more phosphorite, darker color.

Figure 4 shows the areal distribution of graphic mean grain size of total samples. The mean grain size ranges from fine to very coarse sand. The general picture of grain size distribution is as follows. The phosphate rich area is bounded to the north and to the west by coarse sands containing variable but usually slight amounts of phosphate and characterized by iron stained quartz. To the east, slightly beyond the sampled area, is fine to medium grained sand which makes up the Frying Pan Shoals. To the south and east, the sediments tend to be medium to fine grained and grayer in color. Within the phosphate sand area, the grain size distribution is very patchy and ranges from fine to very coarse. The fine sands invariably contain the largest numbers of phosphorite grains and tend to be significantly darker in color. Because of the rapid changes in grain size and the number of samples studied, the map of grain size distribution must be considered to be very preliminary in nature.

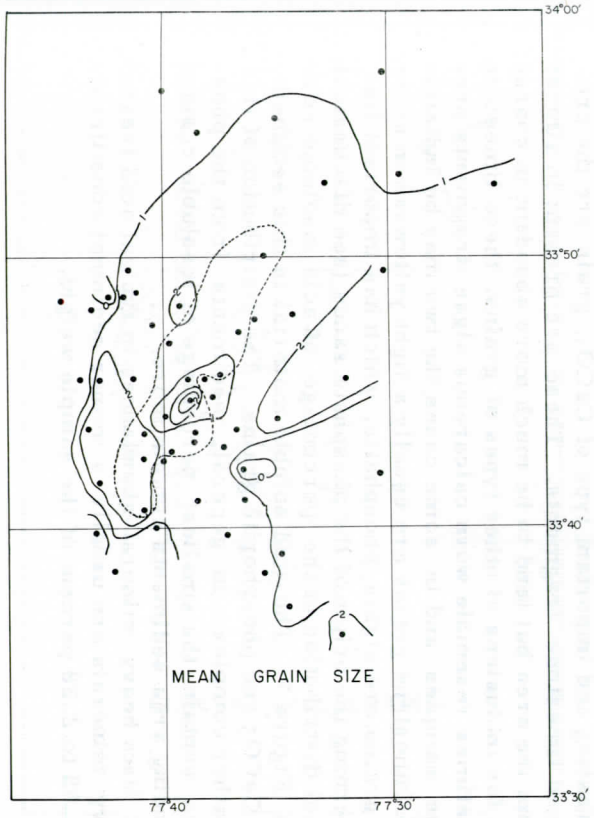

Figure 4. The areal distribution of the mean grain size (Phi units) of total (untreated) sediment. The dashed line is the 4 percent P_2O_5 contour (Figure 9).

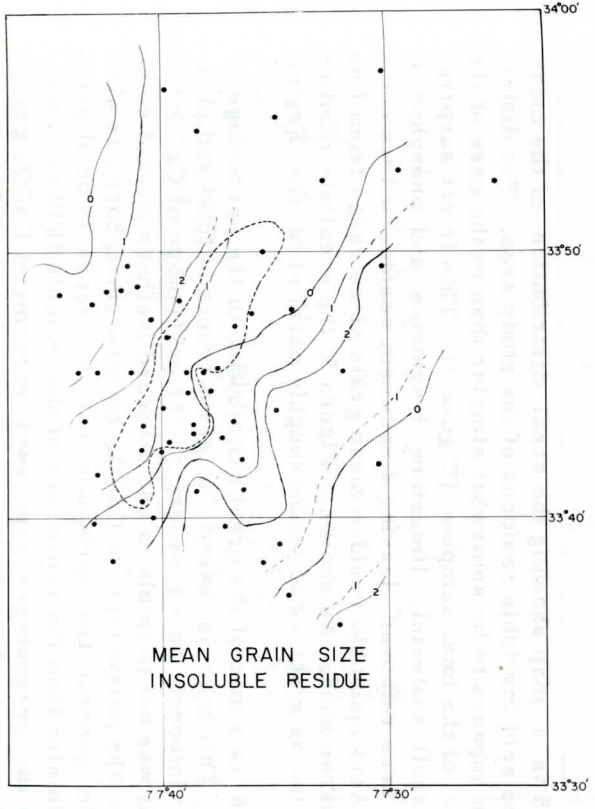

Figure 5. The areal distribution of the mean grain (Phi units) size of acid in soluble residues. The dashed line is the 4 percent P_2O_5 contour (Figure 9).

Figure 5 is a map showing the areal distribution of the mean grain size of the acid insoluble residues of the study area. The distributional pattern appears to be somewhat simpler than in the case of the mean grain size of the total samples (Figure 7). This is not surprising since the shell material, limestone fragments and phosphorite grains have all been removed, leaving a sediment residue of less complex genesis. Acid insoluble residue mean grain sizes range from fine sand to very coarse sand. As shown in Figure 5, the areal distribution can be interpreted as a series of bands roughly parallel to the Frying Pan Shoals.

Figure 6 is a map of the areal distribution of the percentage of $CaCO_3$ grains. This map is based on grain counts of total samples. The counts are intended as a measure of the percentage of $CaCO_3$ in the samples. It was not possible to use standard methods of acid solution to measure the percentage of $CaCO_3$ because phosphorite is also acid soluble. In general the carbonate fraction tends to be slightly coarser in grain size than the remainder of the sample (Pilkey, 1964). Because of this the percentages expressed in terms of $CaCO_3$ grains should tend to be lower than the true weight percent $CaCO_3$. On the other hand, limestone rock fragments, which are counted as $CaCO_3$ grains, contain phosphorite and quartz grains and are abundant in some samples. This might tend to cause the percent of $CaCO_3$ grains and weight percent $CaCO_3$ to be closer. At any rate, the numbers plotted in Figure 8 and listed in Table 1 are rough approximations of the percent $CaCO_3$.

The percentage of $CaCO_3$ grains ranges from about 10 to over 60 percent although most values fall between 10 and 30 percent. The phosphate rich area tends to be low in $CaCO_3$.

An interesting and important type of $CaCO_3$ grain are the previously mentioned limestone fragments. These are present in almost all samples from the area but tend to be much more abundant in coarse sands. Except for inclusions of other types of grains, these limestone fragments sometimes resemble worn calcareous algae fragments present in the same samples and in some cases the two may be indistinguishable. The limestone grains are usually a light yellow tan in color. Some of these grains are highly phosphatic, which has important implications concerning the origin of the phosphate sands (see discussion).

The areal distribution of the percentage of acid insoluble residue is shown in Figure 7. The acid soluble material in this sediment, of course, are $CaCO_3$ and phosphorite grains. The distribution of this parameter is rather complex. In general, sediments from the phosphatic sand area contain the smallest percentage of insoluble residue and the surrounding area sediments contain more.

Table 2 lists heavy mineral abundances in typical acid treated samples. Heavy minerals are usually a minor sediment constituent, ranging from 0.08 to 2.28 percent of the sample weight.

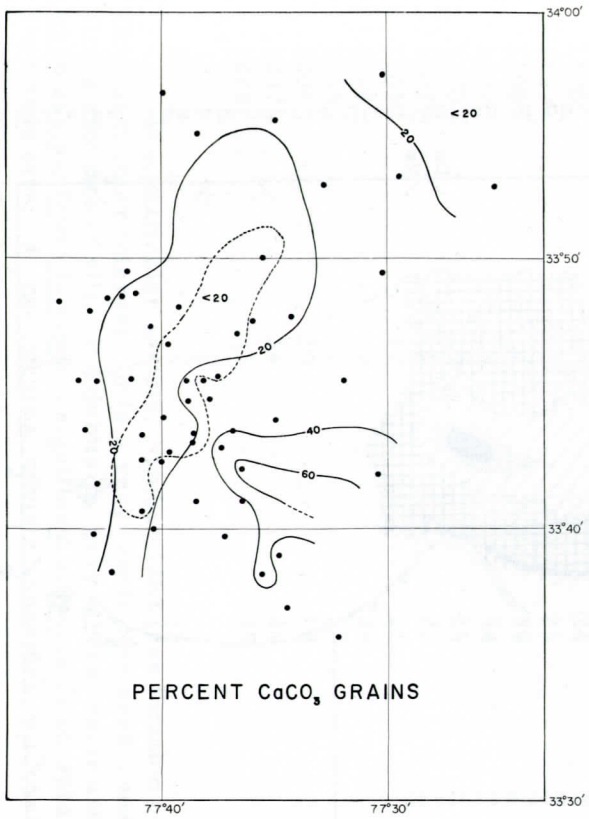

Figure 6. The areal distribution of the abundance of $CaCO_3$ grains as determined by grain count. The dashed line is the 4 percent P_2O_5 contour (Figure 9).

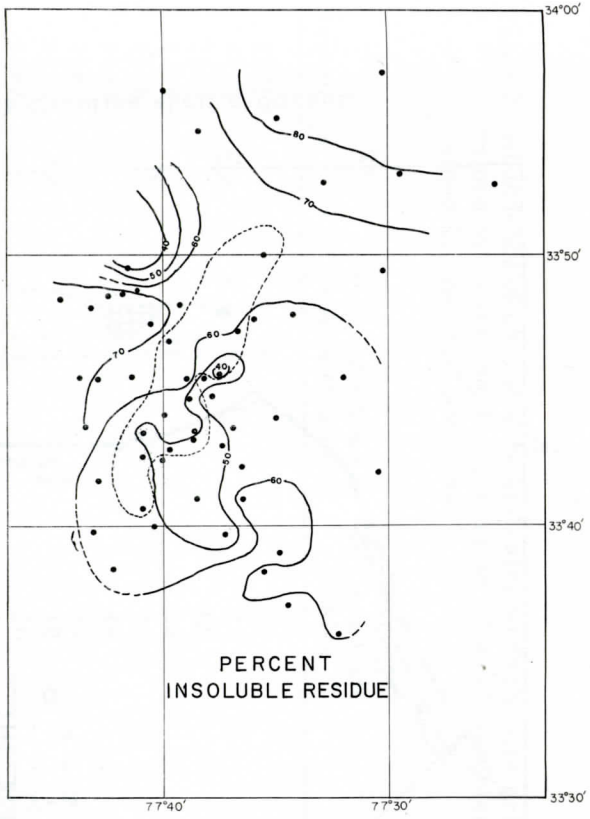

Figure 7. The areal distribution of the percentage of acid insoluble material. The dashed line is the 4 percent P_2O_5 contour (Figure 9).

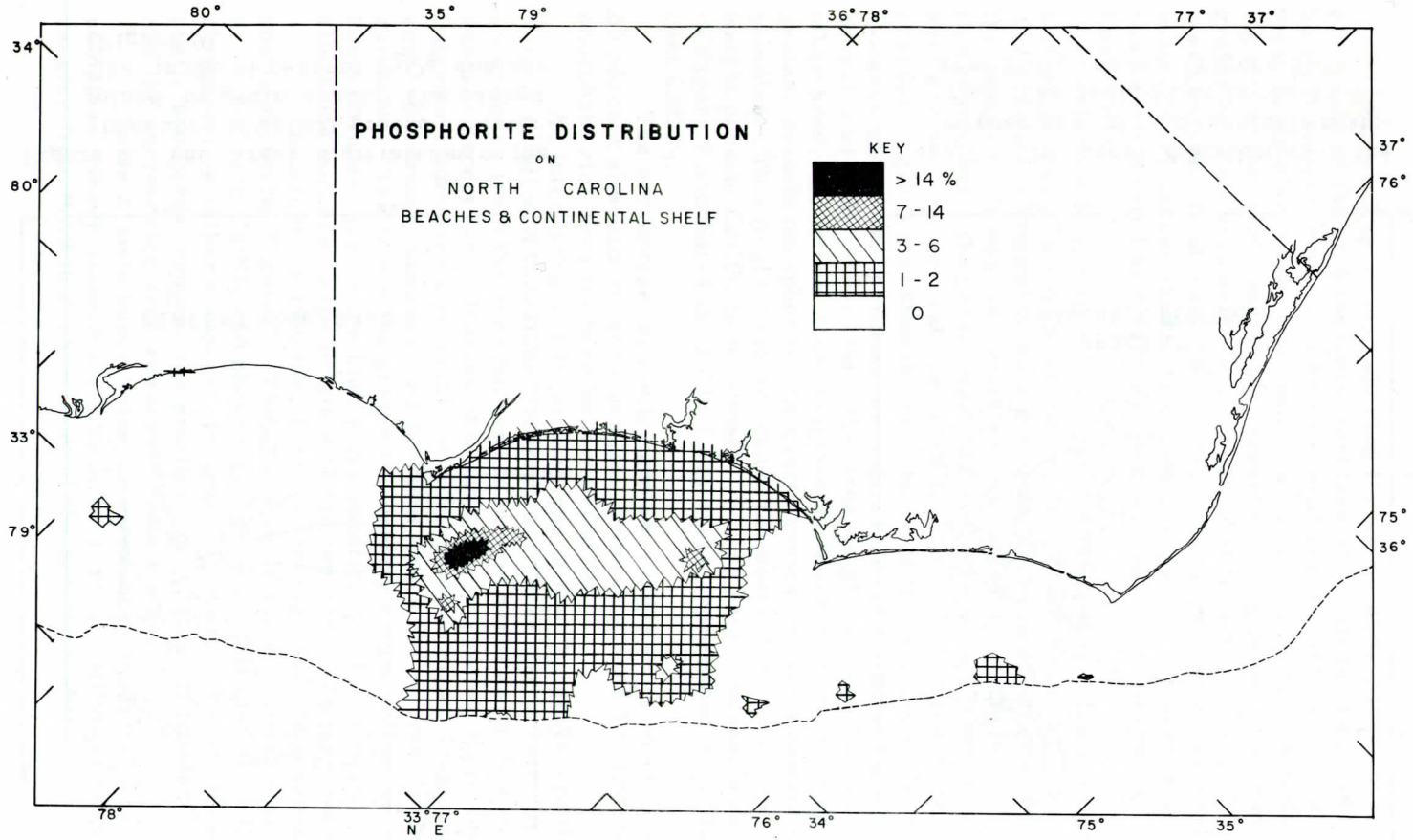

Figure 8. The abundance distribution of phosphorite grains in North Carolina shelf sediment.

Table 1. Abundance of phosphorite and calcium carbonate grains determined by count and P_2O_5 content of total samples as determined by chemical analyses.

Sample No.	Percent Phosphorite Grains	Percent Carbonate Grains	Percent P_2O_5
1171	8	10	0.83
1172	4	24	0.60
1173	40	12	7.78
1174	21	28	3.42
1176	24	34	1.93
1177	38	14	6.97
1180	32	16	6.99
1181	22	10	4.46
1182	19	26	1.33
1183	15	16	0.54
1184	12	29	1.90
1185	5	32	1.06
1186	7	26	1.40
1187	2	27	0.62
1188	8	21	1.70
1189	26	16	7.06
1190	19	31	3.22
1191	19	30	3.66
1195	4	35	1.27
1196	12	24	2.79
1197	3	23	0.73
1198	4	39	1.04
1199	5	54	1.63
1200	25	25	7.12
1202	29	21	4.36
1203	17	11	1.10
1204	3	34	1.36
1205	5	17	1.29
1206	20	18	5.70
1207	34	28	6.54
1208	3	35	1.40

One particular sample, Number 1263 (see location on Figure 1), is of particular interest. It is a very fine to fine sand containing significant amounts of silt. It exhibits a grey green color and is the only grab sample found to contain significant amounts of phosphate, coarser than sand size. A cut of this sample contained well over a hundred

Table 2. Weight percent of heavy minerals in selected acid treated samples from the study area.

Sample Number	Weight Percent Heavy Minerals
1173	0.63
1174	1.15
1176	0.08
1177	1.07
1179	0.20
1180	2.28
1181	1.77
1182	0.18
1184	0.53
1186	1.59
1187	0.24
1188	0.20
1189	0.51
1192	1.83
1193	0.98
1197	0.18

phosphatized sharks teeth and numerous bone fragments, all in the granule to pebble size fraction. Also in this coarse fraction were numerous rounded pebbles of phosphate rock along with some rounded quartz and shale rock fragment particles. The silty sand matrix contains only small numbers of phosphorite grains.

Bottom sonar profiles indicate that rock outcrops are important in the area (Figure 2). Bottom photos indicate that pebble and perhaps cobble sized material is more abundant than indicated by available grab samples. No rock dredges per se were carried out but occasional rocks were found in the grab samples. Of particular interest is a biological trawl taken at station 1267 in which several dozen rock fragments were obtained the largest of which is about 20 cm across Some of the fragments exhibit fresh faces indicating they have been broken off during the dredging operation. All of the fragments were highly pitted and irregular in form due to the activities of rock dwelling organisms and perhaps aided by subaqueous solution. One of the rocks was a fist-sized rounded piece of phosphate rock (phosphatized limestone?). The remainder were slightly friable light yellow to gray fossiliferous limestone. The fossil assemblage appears to be late Tertiary, but more specifically diagnostic macro-fossils in identifiable condition were not found. This limestone contains phosphorite grains. Visual estimates indicated a maximum abundance of close to 15 percent phosphorite grains but 3 to 5 percent is probably more typical. Small limestone fragments with similar characteristics were

noted in several other grab samples. This was the only rock type observed in our samples from the phosphate rich area.

PHOSPHATE

Luternauer (1966) distinguished three types of phosphorite grains in North Carolina shelf sediments. These are a black variety, a reddish brown to amber variety and mottled grains. Mottled grains are sand size quartz grains with "patches" of black phosphatic material covering small portions of the grains. Thin section observation indicated that often these patches filled small, grain surface depressions. Medium to coarse sand size and larger phosphorite grains often contain quartz inclusions. It is likely that the mottled grains are formed by abrasion of these larger grains.

Black phosphorite grains are strongly predominant in terms of abundance in North Carolina shelf sediments. However, in the phosphate rich area off Cape Fear, red brown or amber varieties predominate (Table 3).

Figure 8 shows the distribution of phosphorite in North Carolina shelf sediments. Phosphorite is found almost exclusively in Onslow Bay between Cape Lookout and Cape Fear. Two "highs" can be seen in innershelf sediments, the larger of which is the subject of this report.

The phosphorite grains are believed to be detrital mainly because of a close correlation of quartz and phosphorite grain sizes over the entire North Carolina shelf (Luternauer, 1966) although this quartz-phosphorite grain size correlation is not as close in the Frying Pan

Table 3. The percentage of black and amber phosphorite grains in 15 samples as determined by grain count.

Sample No.	Percent Black	Percent Amber
1258	2	0
1259	1	3
1260	5	6
1261	6	11
1262	8	7
1263	1	0
1264	1	1
1265	1	1
1266	2	2
1267	4	2
1268	4	22
1269	2	39
1271	1	4
1210	2	3

phosphate sand area as elsewhere on the shelf. Also the polish of most of the grains may reflect an abrasional history. Phosphorite grains polish quite readily as shown by tumbling barrel experiments (Pevear and Pilkey, 1966). Further indication of detrital origin of the grains is the sporadic distribution on the shelf in a manner apparently unrelated to changes in water conditions. Last, but not least, sea water chemistry conditions are unlike those in which phosphorite forms at the present time off Southern California and other areas.

If the grains are not of authigenic origin, there are two other likely sources; fluvial or shelf outcrops. Present day river sediments in this area are essentially devoid of phosphorite grains and are thus not believed to be a source. However, it is conceivable that due to increased gradients or other factors, Pleistocene rivers did erode, transport, and deposit phosphorite from phosphatic coastal plain outcrops.

Judging from numerous R/V EASTWARD bottom profiles as well as local fisherman reports, outcrops are very numerous on the shelf of Onslow Bay. This fact, coupled with the previously mentioned sporadic distribution of phosphorite, indicates that an outcrop derivation is feasible. The evidence favoring either Pleistocene rivers or shelf outcrops as the most important source of shelf phosphorite is inconclusive. It is quite possible that both sources are significant.

Figure 9 is a map showing the areal distribution of the P_2O_5 content of sediments in the study area. These figures and others in this paper are based on averages of analyses obtained from several sources. The analyses are of total samples, not concentrates. Excellent agreement between the analytical results of various company laboratories was noted in almost every case. In the construction of Figure 9, grain counts were used to help in interpolating the abundance isopleths in instances where P_2O_5 analyses were not available. Table 1 lists P_2O_5 analytical results.

It is apparent from Figure 9 that the area of phosphate rich sand lies in a band trending NNE and SSW. The band of anomolously high phosphate is a little more than 10 miles long and about 3 to 4 miles wide.

Further information concerning the nature of this phosphorite can be obtained from Figure 10. This figure is a plot of a histogram of the frequency distribution of P_2O_5 in various size fractions (expressed in mesh sizes) superimposed on a histogram of the size distribution of the total sample. The P_2O_5 analyses are of total size fraction samples, not concentrates. The purpose of this is to illustrate the size distribution of the phosphatic content in relationship to the size distribution of the sample. In three out of the four illustrated samples the P_2O_5 content tends to be concentrated in the fines. For example, in sample No. 1173, 22.4 percent of the sample falls in the 48 to 65 mesh range but 47.6 percent of the total P_2O_5 content is in this size fraction. Similarly in sample 1180, 36 percent of the sediment is distributed

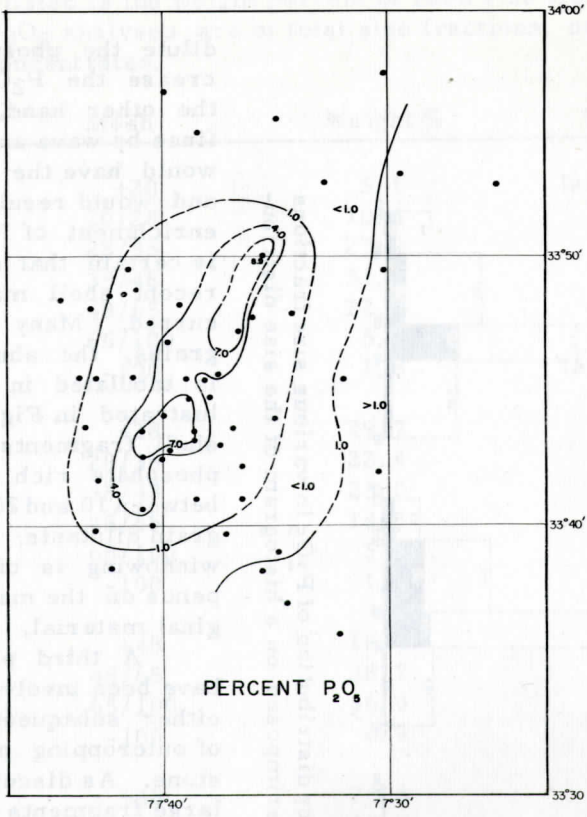

Figure 9. Areal distribution of the percent P_2O_5 in total sediments.

between 65 and 100 mesh but 55.9 percent of the total P_2O_5 is in the same size fraction. In sample 1200 the P_2O_5 tends to be in the coarser size fractions.

Table 4 lists the analytical data on which Figure 10 was based.

No firm figures are available on the P_2O_5 content of a concentrate of phosphorite from this area. Most of the samples sent to various companies were very small and it apparently was difficult to separate a clean concentrate. Particular difficulty was experienced in separating aragonite and phosphorite.

DISCUSSION

Several sedimentary processes must have influenced the composition of the surficial phosphatic sands. One is dilution by calcareous shell material and/or quartz sand from adjacent recent sediment deposits as well as local outcrops. This process would of course tend to

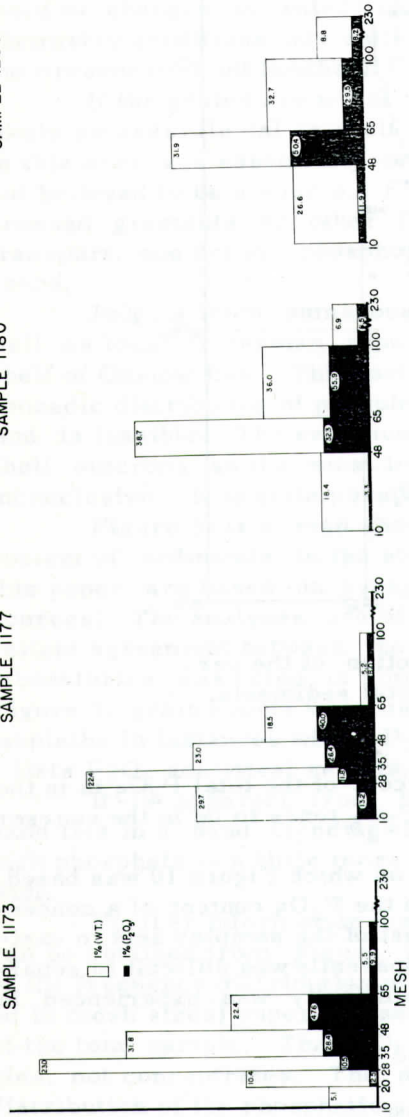

Figure 10. Histogram of the frequency distribution of P_2O_5 in various size fractions expressed in mesh sizes, superimposed on a histogram of the size distribution of the total sample.

dilute the phosphorite and decrease the P_2O_5 content. On the other hand, winnowing of fines by wave and current action would have the opposite effect, and would result in an apparent enrichment of P_2O_5 content. It is certain that some dilution by recent shell material has occurred. Many of the $CaCO_3$ grains, the abundance of which is tabulated in Table 1 and illustrated in Figure 3, are fresh shell fragments. Most of the phosphate rich samples contain between 10 and 20 percent $CaCO_3$ grain dilutants. Whether or not winnowing is of importance depends on the makeup of the original material.

A third process that may have been involved is weathering, either subaqueous or subaerial of outcropping phosphatic limestone. As discussed previously, large fragments of significantly phosphatic limestone were obtained in several grab samples and a biological trawl. Also, coarse sand sized, highly phosphatic limestone fragments are an important constituent of some samples. Since the phosphate rich samples tend to be relatively fine grained, they contain few limestone fragments.

An important observation is that the ratio of amber to black grains in the limestone grains and large fragments is similar to that found in the unconsolidated phosphatic sand. That is, amber grains usually are dominant, which as previously discussed is in contrast to most of the rest of Onslow Bay where black grains are most common.

Table 4. The P_2O_5 content of various size fractions of 4 samples. Also, listed is the weight percent of each size fraction. Note that P_2O_5 analyses are of total size fractions, not phosphorite concentrates.

Sample No.	Mesh	Weight %	% P_2O_5
1173	+20	5.1	less than 1
	20/28	10.4	1.9
	28/35	23.9	3.6
	35/48	31.8	7.0
	48/65	22.4	16.8
	65/100	5.5	14.1
	-100	1.8	less than 5
1177	+28	29.7	3.1
	28/35	22.4	3.7
	35/48	23.0	8.1
	48/65	18.5	15.2
	65/100	5.2	10.8
	-100	1.2	3.1
1180	+48	18.4	1.2
	48/65	38.7	5.8
	65/100	36.0	10.8
	-100	6.9	8.6
1200	+48	26.6	3.2
	48/65	31.9	11 2
	65/100	32.7	6.4
	-100	8.8	6.6

There is no doubt that the phosphatic limestone is at present releasing phosphorite grains to the adjacent sediment. The rock fragments dredged up exhibit a highly irregular jagged outline typical of limestone subjected to significant solution effects during weathering. Although solution may have played a significant role in the subaqueous weathering of these outcrops it is probable that the numerous boring organisms present are of primary importance in this process.

Conceivably, the entire band of unconsolidated phosphate rich sands could be a concentrate, derived by a combination of physical, chemical, and organic processes operating on the limestone outcrop. In fact, in the light of the admittedly sketchy evidence, this appears to be the most likely explanation.

Working on the assumption that the deposit was formed as a weathering residium the question is then how thick can such a deposit

be? This can only be answered by further exploration. If the sub-bottom topography is irregular the deposit could have significant thickness in local or area depressions. If such depressions do not exist, the entire deposit may be relatively thin layer. Another important factor may be whether or not the deposit has formed only recently, or whether the concentration by weathering was going on during the last Pleistocene lowering of sea level, or even previously? If a relatively long time has been involved, it is possible that a significant thickness could have accumulated.

No attempt has been made to correlate underwater outcrops or sediment cover with coastal plain equivalents. The one exception to this is the unusual sample found at location 1263. The nature of the coarse grained phosphate and particularly the few well rounded quartz pebbles is characteristic of Plio-Pleistocene phosphatic sediments of the lower coastal plain.

SUGGESTIONS FOR FURTHER STUDY

Further investigation of this area is definitely warranted. Our preliminary results aid in pointing out possible approaches to such studies. An obvious unknown factor is the thickness of the phosphatic sands. A good approach to this might be the use of some sort of acoustic reflection device similar to that of Moore (1960) on the Southern California shelf. Coring, particularly Vibra-coring, would obviously give an idea as to thickness.

We suggest that an excellent first step would be a reconnaissance investigation by diving. The areas of highest phosphate concentration should be observed first. Perhaps study by a towed or self-propelled skin diver submersible would be helpful. Crisscrossing the areas of interest would immediately reveal the extent of outcroppings of the phosphatic limestone. If rocky areas are fairly ubiquitous then it would be immediately apparent that the deposit is thin. On the other hand, if broad areas without outcrops are present they should then be further investigated by coring devices. Besides the immediate phosphate rich areas; location 1263, should be sampled or observed further.

The study area may also be important from the standpoint of submarine weathering, assuming solution of limestone is occurring. Little is known either quantitatively or qualitatively of submarine weathering processes under the conditions found in this area.

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